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ONR TROPICAL CYCLONE MOTION
RESEARCH INITIATIVE:
FIELD EXPERIMENT PLANNING WORKSHOP

RUSSELL L. ELSBERRY

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Abstract

The Office of Naval Research Tropical Cyclone Motion initiative is a five-year program to improve basic understanding of tropical cyclone motion. On 19 May-21 May 1989, a meeting was held in San Diego, California to continue the planning of a field experiment in the western North Pacific during August and September 1990. The three previous hypotheses were reviewed and a new hypothesis related to tangential wind asymmetries was proposed. The remainder of the meeting was devoted to working group discussions of observational systems (radar wind profilers, satellites, land and ship rawinsondes, aircraft, radars, and surface network) and the experiment forecast support, data management and experiment operations. Summaries of the working group reports are included.

1. Introduction

A five-year basic research program to improve understanding of tropical cyclone motion began 1 October 1986 under the sponsorship of the Office of Naval Research Marine Meteorology Program (R. F. Abbey, Jr., Program Manager). This program involves theoretical studies, analysis of existing observational data, and a field experiment in the western North Pacific region during summer 1990. A series of workshop reports (Elsberry, 1986; 1987a; 1987b; 1988a; 1988b) describe respectively: the planning of theoretical studies; possible observing systems for tropical cyclone studies; a reassessment of the program in view of elimination of aircraft reconnaissance in the western North Pacific during 1987; a review of first-year progress and tentative hypotheses; and a review mid-year progress and the hypotheses and formation of tentative working groups. An update of the progress and plans as of January 1989 is given by Abbey and Elsberry (1989) in the preprint volume of the 18th Conference on Hurricanes and Tropical Meteorology of the American Meteorological Society (AMS).

A workshop was held in San Diego, California on 19-21 May 1989 to plan the field experiment in the western North Pacific during August and September 1990. A list of attendees is given in Appendix A. As the workshop followed the AMS conference, some of the attendees participated only during the first portion. We continue to benefit from the participation of cooperating agencies, such as the Hurricane Research Division (HRD) of the National Oceanic and Atmospheric Administration (NOAA). Dr. T. Muramatsu and Mr. E. Adug were official observers from the ESCAP/WMO Typhoon Committee Special Working Group on Typhoon Experiments. Dr. J. Chan was the observer from Hong Kong and Dr. S. K. Kim was the observer from Korea. Dr. C.-S. Lee represented Taiwan. Three USSR scientists (A. A. Chernikov, I. G. Sitnikov, and P. N. Svizkounov) attended through arrangements by the National Weather Service (NOAA). Presentations by these various groups of their planned activities during August and September 1990 contributed much to the discussions and planning of the ONR field experiment.

The agenda for the workshop is provided in Appendix B. The primary objective of the workshop was to begin planning of the field experiment. The specific goal was to initiate writing the field experiment plan. A tentative outline of this plan (Appendix C) was distributed to indicate the structure. This outline was based on the Experiment on Rapidly Intensifying Cyclone in the Atlantic (ERICA) Field Operations Plan. Copies of relevant segments of the ERICA plan were distributed to Working Group leaders for guidance as to scope and desired content.

R. Abbey of ONR opened the meeting by briefly reviewing the status of the project. The amount of funding to continue the research studies and carry out the field experiment is very limited. Careful planning will be necessary to accomplish the goals of the initiative.

2. Discussion of hypotheses

Some condensation of potential hypotheses from five to three hypotheses had occurred at the previous workshop in Rainbow Beach, Australia (Elsberry 1988b). Nevertheless, the hypotheses were still considered tentative and subject to further discussion and refinement based on recent research. The purpose of this portion of the workshop was to review the hypotheses, which would also provide necessary background for discussions in the working groups. One of the objectives of these working groups was to define the observational network necessary to test the hypotheses. An additional goal was to raise questions that still need to be addressed in the Field Experiment Plan. Some of the questions regarding the adequacy of the network to address some points in the hypotheses may only be answered following the analysis of the experimental data. The discussion by the proponents and opponents on these questions was useful for directing attention to specific analyses that will be necessary or desirable.

A. Hypothesis I (Rapporteur: J. Evans)

This hypothesis may be stated as:

> INTERACTIONS BETWEEN LARGE INTENSE TROPICAL CYCLONES AND THE SUBTROPICAL RIDGE WILL MODIFY BOTH CIRCULATIONS AND CAUSE SIGNIFICANT DEPARTURES IN THE TROPICAL CYCLONE TRACK COMPARED TO AN UNMODIFIED RIDGE-CYCLONE SITUATION.

A useful schematic (Fig. 3, Elsberry 1988a) proposed by G. J. Holland of the horizontal interaction portion of this hypothesis involves the superposition of the so-called beta-gyres on the subtropical ridge to : (i) enhance the anticyclonic vorticity tendency and contribute to a westward extension of the ridge; or (ii) enhance/diminish the anticyclonic vorticity tendency to the east/west and contribute to a poleward turn through the ridge. Recent research has indicated that these gyres depend on the zonal and meridional environmental vorticity gradients, rather than just the earth vorticity gradient (beta). As Bill Gray pointed out, the term beta-gyre is thus a misnomer that leads to confusion. Some term such as "absolute vorticity gyres" may be more descriptive.

The original designation (Elsberry 1988a) of beta-gyre was in relation to the large (500 km) scales of the gyres found in barotropic, nondivergent models in which the only forcing is the earth vorticity gradient (beta). Another type of gyre in these models has a horizontal scale on the order of the radius of maximum winds. The reality of these smaller inner core gyres (called alpha-gyres to distinguish them from the beta-gyres) is still being debated. Willoughby (1988) isolated an instability in a linear model that may contribute to a trochoidal motion of the vortex. Peng and Williams (1989) have studied this instability and indicated that it may be damped in numerical models with inadequate horizontal resolution (say greater than 10 km). Smith *et al.* (1989) also have addressed this question. However, the vortex motion that may occur due to these inner-core processes will not be the focus of the field experiment. High resolution aircraft Doppler data and precise locations of the vortex center each hour for perhaps 8-12 h would be required to explore this

feature. Fictitious gyres on this scale can be introduced in the data analysis by mislocating the storm center relative to the wind observations. This topic is clearly more appropriate to the Hurricane Research Division (NOAA) field program rather than the ONR field experiment.

The presentation of a case study by Dr. Mark Lander of the University of Hawaii illustrated vividly the complexity of the interaction between a tropical cyclone (TC) and the environmental circulations in the western Pacific. One of his examples included a movement through a ridge, an interaction with a Tropical Upper Tropospheric Trough (TUTT) and then with another ridge. The presence of a TUTT cell would indicate baroclinic effects that invalidate the single-layer barotropic assumption in most TC models. The depth of downward penetration of the TUTT cell is indicative of its strength, with some cells extending down to 500 mb. More discussion of baroclinic effects associated with TUTT cells and midlatitude troughs will be given below in the Hypothesis II section.

The discussion relevant to Hypothesis I is whether the observational network will have sufficient horizontal and vertical resolution to resolve the gyres. Wind measurements at the middle levels appear to be essential because upward (downward) extrapolation from the surface (250 mb) level would not be adequate. The ship and additional land rawinsondes at 6 h intervals would provide the complete vertical structures. Hourly wind observations from the radar wind profilers will give the most complete description of such features as TUTT cells, outflow jets and perhaps the gyre structure. A key assumption to be tested is the applicability of the Taylor hypothesis for converting the hourly profiles to spatial variations. C. Velden and colleagues at the University of Wisconsin and HRD (NOAA) have combined 350 mb and 850 mb wind fields and TIROS soundings to define midlevel fields. Unfortunately, the water vapor imagery on the USA geostationary satellite that C. Velden used to increase data in the midlevels is not available in the western Pacific region.

Michael Reeder of the University of Munich group reported that the gyres could not be detected reliably by extracting simulated soundings from a barotropic model field at just the locations in the previously proposed observational network. However, Jenni Evans of Monash University stated that the gyres were well defined in her simulations with a divergent barotropic model. Greg Holland reminded the participants that he had detected the gyres from the Australian Monsoon Experiment network and that J. Chan had demonstrated the gyre structure evolution from operational wind analyses in the large, slowly moving Typhoon Abby. Analyses of Omega dropwindsonde observations by S. Lord and colleagues of HRD have also revealed the gyres. Bill Gray's composite data sets clearly indicate the gyre structure.

The hypothesis as stated implies that the time changes in the gyre structure would be measured. This is clearly more difficult than simply diagnosing the presence of the gyre (orientation and amplitude) at different times. For example, aircraft data have to be composited relative to the storm center motion over the

time of the flight observations. Extensive time-to-space conversion of the radar wind profiler observations also would require a steady-state assumption, which is inconsistent with deriving the time evolution.

Much of the above discussion is based on vorticity dynamics. Vorticity is, of course, a derivative of the wind field. Consequently, the first focus should simply be to observe the TC-ridge interaction. The working groups need to verify that the observational network is sufficient to describe the TC-ridge interaction region. If so, the secondary features such as gyres should follow. The conclusion at the previous workshop was that the interaction could be defined by the observational network without aircraft, provided that the center position and outer wind structure of TC could be resolved by satellite data, rawinsondes and radar wind profilers.

One factor in examining the adequacy of the network is the speed of the TC around or through the ridge. Translation speeds as the storm passes around the ridge line are typically about 5 kt, although cases with faster translation certainly occur. The larger the propagation vector relative to the steering current, the more likely that the component will be detected. Wind observation accuracies of a few knots over 500 km will be difficult to achieve. A jet aircraft with dropwindsondes would be very useful in this regard. Even some aircraft data in the midlevels around the periphery of the storm would also be helpful.

B. Hypothesis II (Rapporteur: L. Carr)

Much of the above discussion also relates to this hypothesis, which may be stated:

> Significant turns in the tropical cyclone track occur when the interaction with transient synoptic-scale features, such as midlatitude troughs or TUTT cells, causes a response that extends the effects over a deep layer.

Recurvature of the TC in association with a midlatitude trough is the most obvious example, and one of considerable importance because of the potentially large track forecast errors. This process is very sensitive to the relative positions of the trough and the TC, and to the vertical extent of the midlatitude trough. One alternative to the recurvature scenario is that the midlatitude trough will sweep past the TC, which will then continue on a westward track or perhaps even to the southwest. Another alternative is that the midlatitude trough will be directly over the TC, and the TC may then become quasi-stationary.

Although the TC and trough are synoptic-scale features, the interaction between them may occur on relatively short time scales. Recent analyses of the Australian Monsoon Experiment data by G. J. Holland indicate that the interaction excites a type of normal mode response in the upper levels that propagates down and modifies the flow in lower levels.

It is convenient to group the interactions with TUTT cells in this hypothesis although the horizontal scales are smaller. As above, the case study presented by

Mark Lander indicates that the TUTT scenario can be quite complex. The position and relative translation of an intense cyclone cell within the TUTT may be more important that the overall TUTT location. Modifications of such a TUTT cell due to interaction with the warm air in the outflow jet of the TC are possible because the cold cell may not be very deep or very large relative to the size of the warm high above the TC.

The operational techniques for detecting TUTT cells involve ad hoc aircraft reports, inferences from satellite imagery and occasionally rawinsonde time sections. Post-analysis of the geostationary satellite imagery may give some midlevel cloud vector winds. As mentioned above, the radar wind profiler observations are expected to provide enhanced observations of the wind structure in TUTT cells and midlatitude cyclones. The ship and additional land station rawinsondes at 6 h intervals will also increase the data coverage.

Even though the planned network will detect many aspects of the interaction, detailed observations of the transient features will depend to some extent on fortunate placement of a radar wind profiler, ship or land station. To maximize the likelihood that the interaction regime will be observed, the NASA DC8 equipped with dropwindsondes would be the ideal platform. The strategy would be to fly along the expected "interaction axis" rather than trying to map the entire trough or TUTT. The high altitude (maximum 42,000 ft) and long endurance (12 h) of the DC8 would allow adequate time to probe the details of the interaction process.

C. Hypothesis III (Rapporteur: J. Evans)

This hypothesis is that:

> A LIMITED SET OF PROPAGATION VECTORS, WHICH ARE THE DEPARTURES OF THE STORM MOTION FROM A SPECIFICALLY DEFINED FLOW, MAY BE DEFINED FOR PARTICULAR CYCLONE CHARACTERISTICS AND ENVIRONMENTAL CONFIGURATIONS.

At previous workshops (Elsberry 1988a, 1988b), the environmental steering flow was specified as the wind averaged between 850 and 300 mb in the radial interval 5-7 deg. lat. around the storm center. The hypothesis is that a small set of propagation vectors could be defined for stratifications by cyclone characteristics (such as size) and/or environmental flow conditions (such as environmental shears or vorticity gradients). Again, the above discussion related to Hypothesis I is relevant to this hypothesis.

Lester Carr presented a summary of a paper by Carr and Elsberry (1989) that includes calculations of propagation vectors from previously published composite data sets. These vectors are westward and generally poleward relative to the steering currents in both hemispheres, which indicates a consistency with the beta-effect. However, the propagation vectors rotate systematically from before, during and after recurvature (except for the latter vector in the Southern Hemisphere). Their interpretation is that environmental vorticity gradients (rather than just beta) could account for these propagation vectors. They recommend that

future stratifications include the outer wind strength in the TC. They also note that misplacing the storm center by 20-40 km will tend to bias the symmetric flow into the asymmetric component near the center.

T. N. Krishnamurti showed the propagation vectors relative to the vertically-averaged winds in his high resolution baroclinic model. These vectors were systematic in time throughout the integration. He cautioned that the magnitude and orientation of the propagation vectors are dependent on the physical process parameterizations in the model. More testing of the sensitivity to various forcing terms is planned on this case and additional real-data cases from the western North Pacific area.

Bill Gray commented that it is easier to measure storm asymmetries in his composite data sets than it is to calculate the propagation vectors. He has now processed 20 y of western North Pacific TC cases compared to the 10 y set that Carr and Elsberry (1989) used. These sets clearly indicate that some other effects than just beta are involved in the propagation vectors.

Model studies by DeMaria (1985), Evans *et al.* (1989), Chan and Williams (1989), Shapiro and Ooyama (1989) and Smith *et al.* (1989) all demonstrate the track deviation associated with environmental vorticity gradients. The question is over what horizontal scale the gradients of environmental vorticity should be calculated. Extracting gradient estimates over the inner 300 km will be subject to error if the vorticity gradient associated with the TC is not removed properly. Jenni Evans was not successful in estimating the vorticity gradients from a cubic surface fit on a 9 x 9 grid with 150 n mi resolution using an empirical orthogonal function representation of U. S. Navy operationally analyzed fields.

Research on this topic should continue from the observational studies and the numerical models to guide the calculations of the environmental vorticity gradients from field experimental data.

D. New Hypothesis (Rapporteurs: J. Evans and L. Carr)

Bill Gray has continued the study of composite data in both storm-motion and geographical coordinates. The tangential wind averaged over the 850-300 mb layer is asymmetrically distributed relative to the center in the storm-motion coordinate system. Winds are stronger (weaker) in the right and front quadrants within (outside) 3 deg. lat. radius. His proposed hypothesis (to be developed in more detail in the future) is

> CHANGES IN TROPICAL CYCLONE MOTION IN THE NEXT 24-48 H ARE A RESULT OF CHANGES IN THE TANGENTIAL WIND ASYMMETRIES THAT OCCUR FIRST AT OUTER RADII AND PROGRESS INWARD WITH TIME.

For example, the front minus back wind asymmetry is reduced for recurving storms, but is maintained for straight-moving storms. Magnitudes of up to 10 m/s are found, whereas the right minus left asymmetry may change 6-8 m/s over 24 h.

These environmental wind asymmetries may be more more important than the beta-effect. In the western North Pacific, the storm motion is to the left of the steering flow. However, the west-moving Atlantic storms track to the right of the steering flow. This difference is believed to be due to formations within the monsoon trough for western Pacific storms, whereas the western Atlantic storms are in the trades well poleward of the monsoon trough. Consequently, the differences are related to the environmental vorticity patterns.

Bill Gray proposes that measurements of the tangential wind asymmetries in inner (approximately 2 deg. lat. radius) and outer (approximately 6 deg. lat. radius) annuli be obtained each 24 h. An aircraft would be essential for the inner radius measurements and perhaps to fill in gaps between ship or land stations in the outer band. Although Bill Gray suggested that geopotential height fields could also be used to describe the asymmetries, Hugh Willoughby stated that his measurements of height asymmetries in Atlantic hurricanes were not well related to wind asymmetries. An aircraft Doppler would probably be very effective in measuring the inner radius wind asymmetry. Gray has submitted a preliminary proposal for the National Center for Atmospheric Research (NCAR) Electra to test this hypothesis during the field experiment.

The discussion of this preliminary hypothesis focussed on the relationships to the other hypotheses. The tangential wind gradients from front to back and from right to left may be related to the vorticity gradients in Hypothesis III. In particular, the variations in the steering flow are related to the shear. As the storm moves into the recurvature area, the shear would also evolve. Similarly, interactions with adjacent synoptic features would change the environmental shear distribution with time. Consequently, some additional discussions of this new hypothesis are necessary to determine if it is really a separate hypothesis or is a subset of the phenomenon-based Hypotheses I and II or the propagation vector Hypothesis III.

3. Working group reports

As indicated in the agenda (Appendix B), the working groups began discussions on 19 May and reported to the entire workshop at various times. The general format of the working group activities was:

(i) Discussion of status;

(ii) Identification of data streams during Intensive Observing Periods (IOP) and non-IOP periods;

(iii) Identification of issues that require group discussion and items that require attention in the future;

(iv) Identification of personnel requirements;

(v) Formulation of budget estimates; and

(vi) Setting a schedule and assigning responsibilities for drafting the Field Experiment Plan.

Items (i) and (iii) will be summarized below. Item (ii) was provided to the Data Management Group. The remainder of the items are still tentative. The working group reports below were prepared by the person listed as Chair and should be regarded as preliminary reports. More definitive plans will appear in the Field Experiment Plan to be published later.

A. Upper air network

Johnny Chan (Chair), Duane Stevens, T. N. Krishnamurti, Bruce Morton, Jim Countryman, Cheng-Shang Lee, Ellaquim Adug, Igor Sitnikov

1) Introduction

The basic consideration in the choice of additional upper-air sounding sites is to set up a network such that a regular latitudinal/longitudinal grid can be approximated. Such regularity is beneficial in diagnostic studies as well as data assimilation procedures. Another important consideration is that any additional sounding sites requested from Members of the Typhoon Committee or from the USSR must be in a location compatible with the objectives of their respective experiments. In the choice of new land stations, local conditions such as different types of supplies (electricity, water, food) must also be considered. The proposed network is described first with an indication of the potential problems. Recommendations as to how some of these problems may be resolved are proposed. Issues that are outstanding are highlighted.

2) Proposed network

The existing upper-air sounding network together with the locations of proposed additional sites are shown in Fig. 1. If all of the additional sites can be deployed, the goal of a "semi-regular" grid can be achieved for the ocean area north of 20° N. The current status of these proposed sites is described below.

(a) USSR Ships. The three USSR ships along 20° N at 126° E, 131° E and 136° E appear to be very certain. However, the schedule of their deployment still needs to be discussed. As indicated in Fig. 2, the fleet will leave Vladivostok around 15 July 1990 and arrive at their respective locations at 20° N in about 1 week. After one day of intercomparisons among them, the ships will traverse south to 13° N and then back to their stationary locations (Fig. 3). This loop will require about 7-8 days so that the ships are ready for the experiment on 1 August. These ships will maintain stations in these locations (unless winds exceeding 24 m/s are experienced, in which case they will evade) for a period of 15 days. The ships will then have to re-supplied. Depending on the location of the supply port, the ships will be away for

about 7 days. They will then perform their southward traverse to 13° N again before resuming the stationary positions. Presently, the plan is for the USSR ships to be re-supplied in Singapore, which means that they will be away from the experiment area for a period of 7 to 8 days. If a closer port such as Manila can be used, the time absent will be less.

With this schedule, the fleet will have to be re-supplied twice during the two months of the experiment. If the ship schedule could be adjusted as in Fig. 2b to begin the first southward traverse after 1 August, it is possible that only one re-supply period would be necessary prior to 30 September. With this revised plan, the time that the USSR ships would be within the experimental area would be a maximum. They would be launching rawinsondes even while traversing the loops in Fig. 3 and thus would be contributing to the database. It is recommended that the Experiment Director make this proposal to the USSR Experiment Committee. (Note: this proposal appears acceptable to the USSR as of July 1989).

A fourth ship is desirable at 20° N, 141° E to provide a regular grid spacing of around 5 deg. lat. along 20° N. This is preferable to a location south of the other three ships (say, around 15 N) because such a location will not contribute very much to improve the scarcity of observations for the area south of 20° N. It is also suggested that the Experiment Director make a request to the USSR Experiment Committee for this fourth ship. (Note: In July 1989, the USSR announced all four ships will be available.)

The USSR ships will make 6-hourly upper-air soundings at 00, 06, 12, and 18 UTC when the tropical cyclone is within 500 km of the ship. The frequency of observations may be increased to 3 h if requested and when the cyclone is within 300 km of the ship. However, if the wind speed exceeds 20 m/s, no soundings will be made.

(b) JMA Ships. The Japanese Meteorological Agency (JMA) has proposed to the Typhoon Committee that one to two vessels will be available during the Typhoon Committee Experiment. If one ship is available, it will most likely be located around 29° N, 135° E. The extra ship will be located either south of the first ship at around 25° N or in the East China Sea near 28° N, 126° E. The first site (25° N, 135 E) is preferred to contribute to the latitudinal/longitudinal grid.

(c) Land Stations. Based only on the primary consideration (i.e., a regular grid), the two land stations that should have the highest priority are in the Bonin Islands and northern Luzon. However, several issues need to be addressed. To use the U.S. military to deploy a station in the Bonin Islands will need the consent of Japan. The working group felt that if the consent cannot be obtained it is worthwhile to spend the resources of the project to deploy a civilian team to the

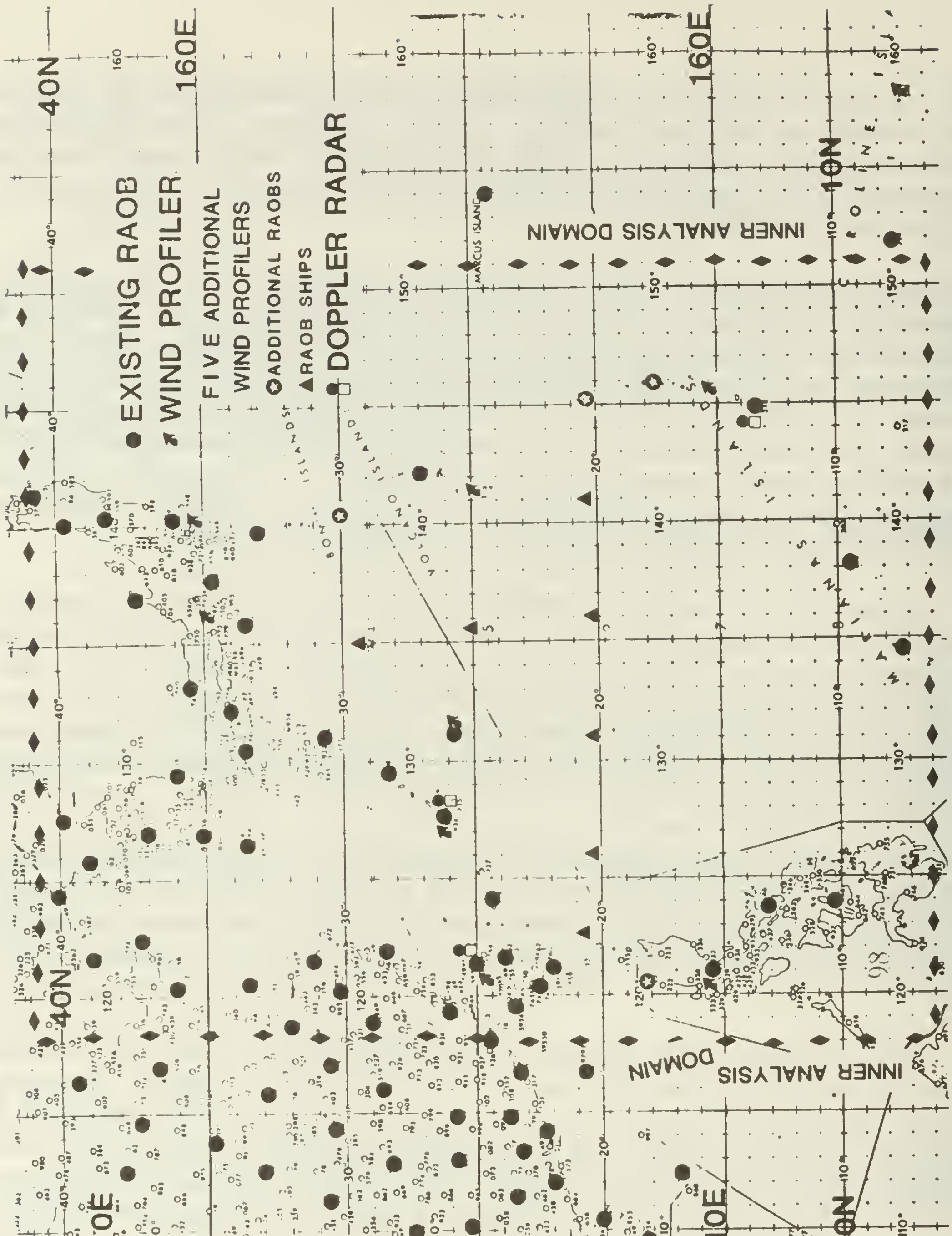
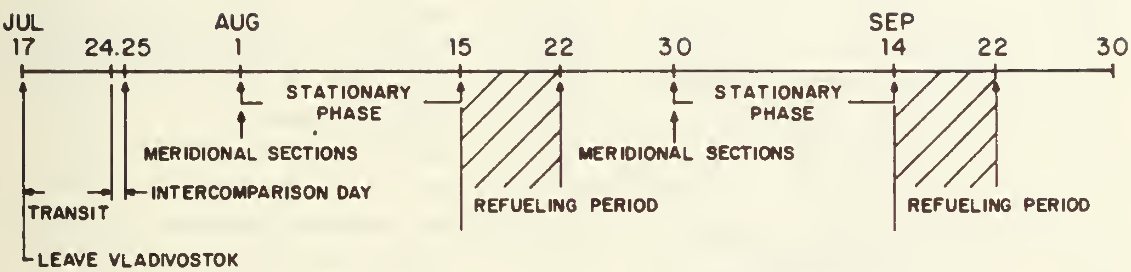


Fig 1. Tentative distribution of wind profilers (arrows), additional rawinsondes (circled stars), rawinsonde-launching ships (triangles) and Doppler radars (open box with circle above) to be added to existing rawinsondes (solid dots). The inner analysis domain for the final analyses is indicated by the diamond enclosed boundary.



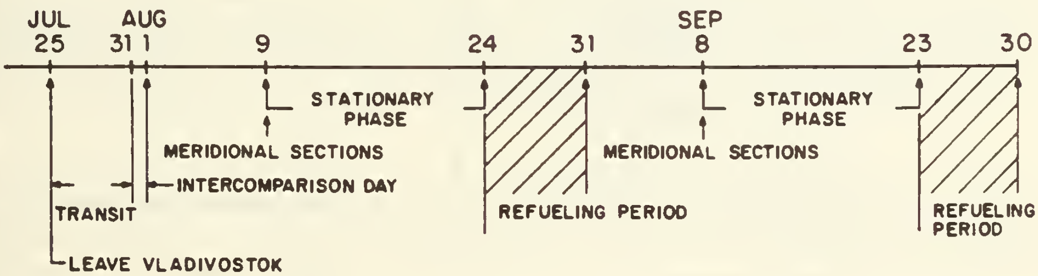


Fig. 2. Preliminary plan (top) and proposed revision (bottom) of the USSR ship deployment schedule (see text for explanation).

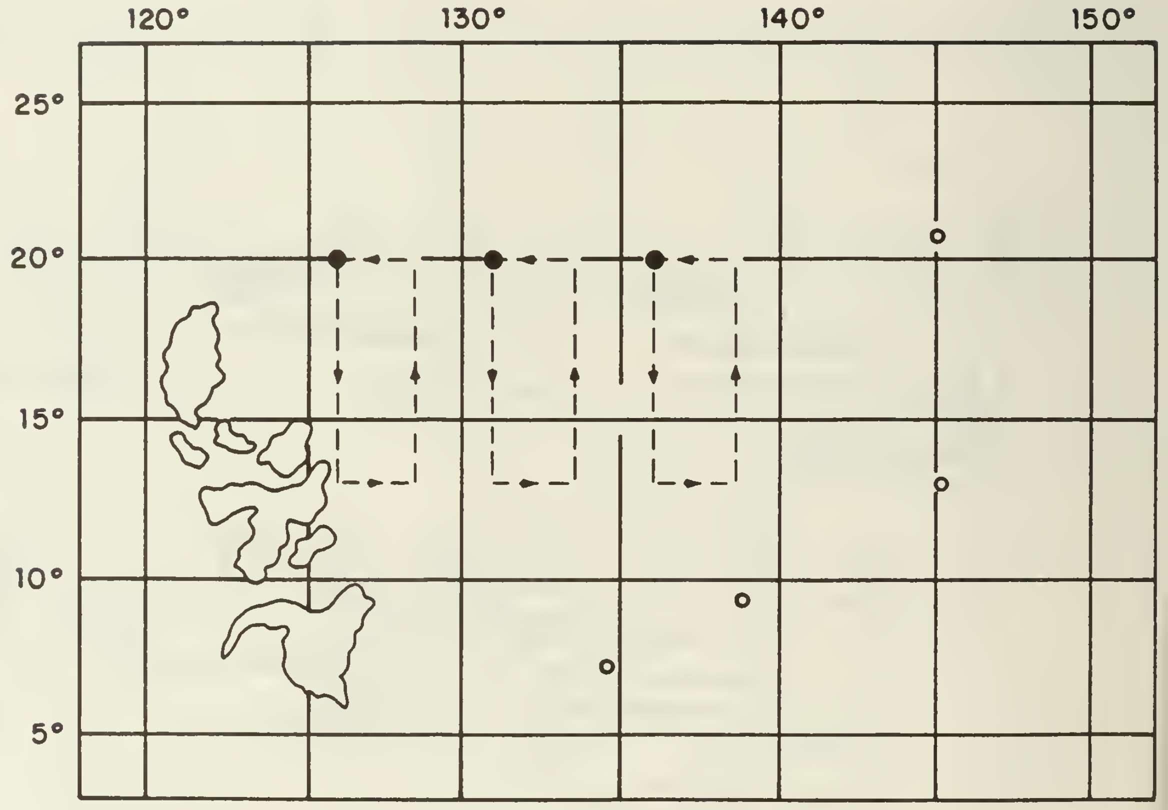


Fig. 3. Stationary positions (dots) along 29° N and transit paths (arrows) along loops to be completed by USSR ships at beginning of each cycle shown in Fig. 2.

station in the Bonin islands. As for the station on northern Luzon, deployment may be uncertain due to safety considerations. It is recommended that the Experiment Director communicate to PAGASA the desire to have this station fully operational during August and September 1990 and to offer whatever assistance is possible.

If one upper-air station can be deployed either on Pagan Island or Farallon De Pajaros Island in the northern Marianas, the southeastern part of the network will be well covered. The choice of which island will depend on the logistics, although the group prefers Farallon De Pajaros as it is closer to the regular grid of the network.

3) Data streams during IOP and non-IOP periods

Testing the hypotheses in Section 2 requires an analysis over an extensive area around the TC. Every effort should be made to acquire upper air soundings regularly (00 and 12 UTC) and during Intensive Observing Periods (IOP). The domain of these analyses should be bounded by 5° N and 40° N between 120° E and 150° E. Thus the western boundary includes stations through the Philippines, Taiwan and along the east coast of China. During an IOP period, all rawinsonde stations within the area will be requested to make 6-hourly observations. It is expected that a 24 h lead time will be given to the stations prior to any IOP for setting up the necessary equipment and personnel. During non-IOP periods, these stations will have their routine 12 h observations. It should be noted that the Typhoon Committee has an established procedure for 6 h soundings when the typhoon is within 500 km of striking one of its Members. Potential conflicts may result if these Members also are requested to make 6 h soundings within the above experimental domain as well. Notice that approximately eight IOP's are expected during August and September 1990. If the duration of each IOP is 48 h, this requirement is for four additional (06 and 18 UTC) rawinsonde launches during an IOP. The total number of additional launches is thus 32 to meet the requirements. Financial assistance may be necessary in some cases to achieve this schedule.

The rawinsonde launches will be transmitted primarily through the GTS network for the regular rawinsonde sites. For the additional sites, communication equipment will have to be acquired to transmit the data to Guam before being relayed onto the GTS circuits. Local backup of the data is essential in case communication in real time fails.

It is rather difficult to compare the data obtained from different types of rawinsondes. However, the meeting agreed to look into the possibility. Failing that, a pre-experiment test could be arranged during which the data can be quality-checked using established numerical procedures, such as at the European Center for Medium-range Weather Forecasts.

B. Radar wind profiler

Bill Frank (Chair), Wayne Schubert, Ken Gage, Werner Eklund, Michael Reeder, Russ Elsberry

1) Overview

The profiler working group is coordinating all of the ground-based remote sensing equipment for the experiment with the exception of the conventional Doppler radars. The group reviewed the status of equipment proposed for use during the field program and discussed the necessary steps and priorities required to implement the deployment. Profiler systems already exist at Kyoto University and Meteorological Research Institute (MRI) in Japan and at Taiwan and Ponape, and data from these systems will be integrated into the experimental data set. Most of the efforts of the working group are concerned with the four or five systems that will be deployed especially for the field program.

2) Status of Equipment

The existing profiler systems are listed below. The locations are shown on the data network map in Fig. 4.

(i) Kyoto University (50 MHz) This is a research facility that is not designed to support full-time operation of the profiler.

(ii) MRI, Japan (405 MHz) This system is being tested for operational potential and is expected to be operated full time during the Typhoon Committee experiment.

(iii) Taiwan (50 MHz) This system will be upgraded to operational status by 1 July 1990 and should operate continuously during the field program.

(iv) Ponape (50 MHz) This NOAA Aeronomy Laboratory profiler will be upgraded by the time of the experiment.

In addition to the above, the following remote sensing systems are proposed for deployment. All of the systems are considered to be available with a high degree of probability, with the exception of the last one listed (Clark AFB).

(i) Saipan (50 MHz and 915 Mhz) This profiler will be operated by Penn State. Other equipment to be deployed on Saipan are a microwave radiometer (measures temperature and specific humidity), a Radio Acoustic Sounding System (RASS) for low-level temperature soundings, ceilometer (cloud base height), 94 GHz cloud radar, Infrared thermometer (cloud base temperature), and possibly a rawinsonde system.

(ii) Iwo Jima (50 MHz) This profiler will be operated by the NOAA Aeronomy Laboratory and BMRC Australia.

(iii) Minamidaito-jima (405 MHz) This system will be operated by Colorado State University.

(iv) Kadena AFB, Okinawa (405 MHz) This Naval Postgraduate School profiler will be equipped with a RASS to obtain low-level temperature profiles.

(v) Clark AFB, Philippine Islands (405 MHz) If sufficient funds and personnel are available to support the deployment of this profiler, it will be operated by Penn State.

3) Site Selection and Restrictions

The proposed island locations of these systems resulted from a combination of scientific and logistical considerations. The 50 MHz profilers are prevented from operating in the Philippines or on Okinawa, and, perhaps on Minamidaito-jima, due to frequency restrictions. It was considered desirable to locate the 50 MHz systems near the periphery of the network to allow them to monitor the passage of upper-level outflow jets as much as possible. The choice of Saipan (or Tinian) for the Penn State system was based on the better opportunities for sampling convection and outer typhoon rainbands at that site relative to Iwo Jima. Transportation and power requirements along with personnel and maintenance needs prevent operation of the systems on extremely remote islands. Overall, it is the opinion of the profiler working group that the proposed island locations are now fixed.

The exact profiler site upon each island is yet to be determined. The profilers on Okinawa and at Clark AFB in the Philippines will be situated on U.S. military bases, and immediate selection of the sites is not critical. Two tentative sites have been selected on Iwo Jima. Tentative sites for Minamidaito-jima will be chosen soon following receipt of information from Japanese authorities. A tentative location near the airport on Saipan has been selected. The next step will be to dispatch a site visit team as soon as possible to make final site decisions at the five locations.

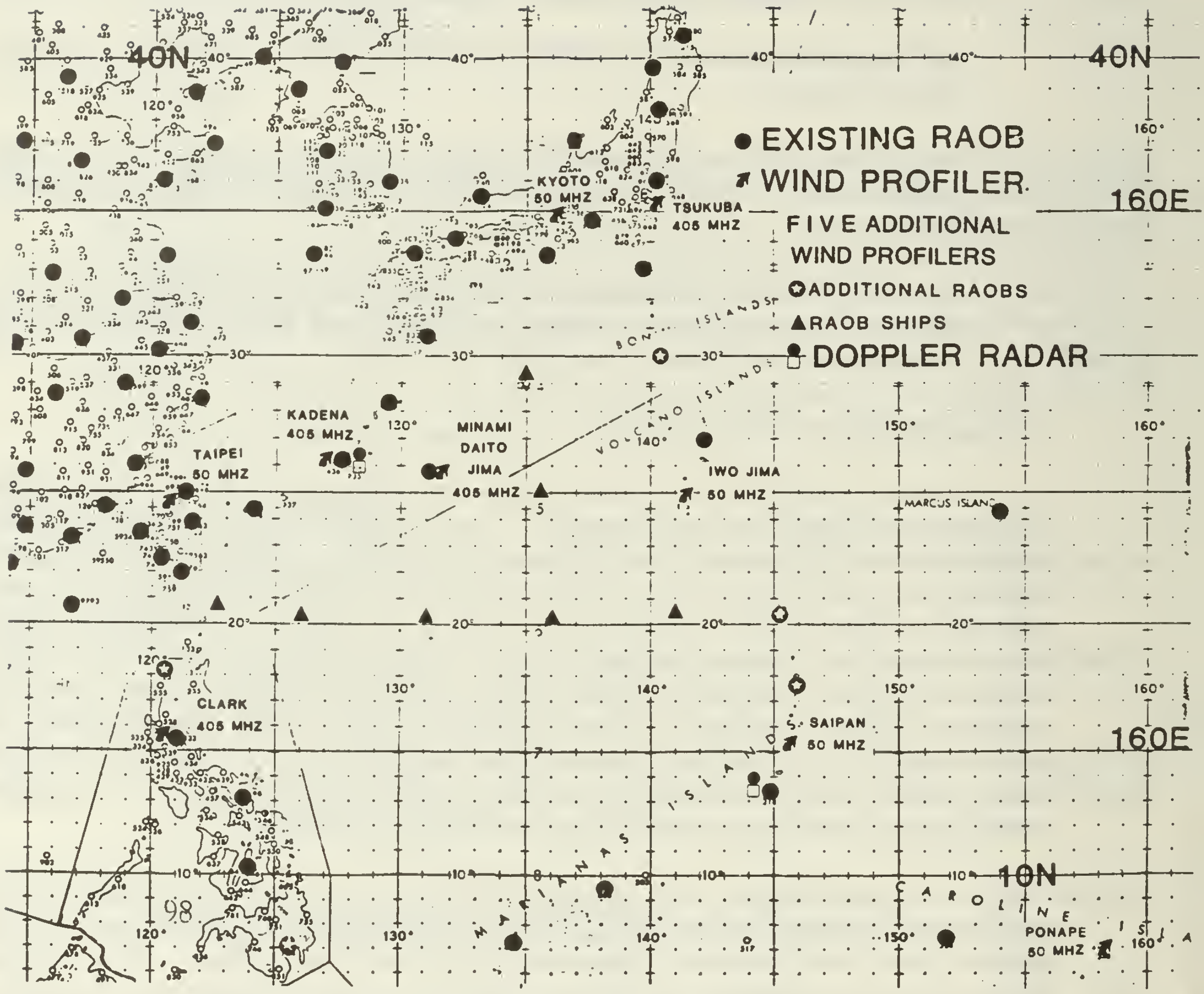


Fig. 4. As in Fig. 1, except indicating locations and frequencies of the radar wind profilers.

4) Frequency Licenses

As soon as tentative sites have been chosen for the five profiler systems, requests for operating licenses will be requested from the relevant authorities. The 20th Weather Wing will request licenses from Japan for the 405 MHz systems on Okinawa and Minamidaito-jima and for the 50 MHz profiler on Iwo Jima. Penn State will request licenses from the U.S. military for the 405 MHz system in the Philippines and for the 50 and 915 MHz profiler and 94 GHz cloud radar on Saipan.

5) Deployment Logistics

Each operating unit will arrange and pay for its own transportation to the field. The USAF 20th Weather Wing will be approached to assist in arrangements for a USAF C-130 to be available to fly equipment into Minamidaito-jima and Iwo Jima.

Site preparations will also be the responsibility of each operating unit. Colorado State will negotiate for the necessary work on Minamidaito-jima with civilian contractors. Discussions are currently underway as to the availability of resources from the U.S. military construction battalions (CB's) to assist in site preparation for the Clark AFB, Okinawa and Saipan sites. The NOAA Aeronomy Laboratory will negotiate with the Japanese military personnel on Iwo Jima for their assistance in grading the antenna site. Each unit will also handle the installation of its equipment, except that members of the Penn State team will assist with the installation of the NOAA/BMRC profiler antenna on Iwo Jima.

6) Operating Plan

The goal is to have each of the five profiler systems deployed for the field program and operating by 1 July 1990, which is one month before the field program officially begins. The units would operate continuously throughout the two month field program and would remain in operation until 31 October 1990, or one month after the official end of the field phase. Operating procedures for the other instruments at the profiler sites have not been agreed upon.

The Taiwan profiler should be operating continuously after 1 July 1990. A request will be made to MRI to operate its profiler continuously during the experiment, and Kyoto will be asked to provide hourly wind profiles during the eight Intensive Observing Periods. The Ponape profiler should be operating continuously throughout the experiment.

The exact vertical levels and parameters to be archived will be determined during the month of operations prior to the beginning of the field experiment. Wind data and related variables will be archived at approximately six minute intervals. Hourly-averaged wind data will be transmitted in real time from each of the five experimental sites and possibly from Taiwan, Ponape and MRI. The winds will be in pibal format. The preferred mode of transmission is via the GTS system. This would require access to the system (permission is currently being sought) and satellite communication devices, which would probably cost the project about $4,000 per site. If permission to use GTS is not obtained, we will attempt to establish phone links to transmit the hourly wind data to Guam. There are no plans to transmit data other than hourly winds in real time.

C. Satellite

Chris Velden (Chair), Robert Merrill, Charlie Holliday, Chip Guard, Ray Zehr, Steve Pryor

1) Satellite status

No major changes have occurred since the previous workshop (Elsberry 1988b, Table 3). The Japan GMS-3 will be replaced by GMS-4, which has identical meteorological capabilities. The new JMA satellite processing schedule includes enhanced operational wind sets four times per day. A special low-level cloud drift wind set is produced at 04 UTC from 15 min imagery. The USA NOAA-10 will be replaced by NOAA-12 during Spring 1990, but no differences in meteorological products are anticipated. Two important changes have occurred with this polar orbiter system. The soundings from the radiometers aboard these satellites are now derived from a physical retrieval method that is similar to the University of Wisconsin technique. Furthermore, the horizontal resolution is now 75 km rather than 250 km. The next Defense Meteorological Satellite Program (DMSP) system will carry a microwave imager (SSM/I) identical to the SSM/I on the present system. Soundings from the DMSP may also be derived via the physical retrieval method by the time of the experiment.

The status and availability of satellite products from the USSR is unknown. One of the USSR ships does have satellite receiving equipment.

2) <u>Guam reception and display capabilities</u>

Although NOAA-10 high resolution imagery may be received in real time from orbits within 1500 n mi of Guam, only selected passes are acquired. This high resolution visible/infrared imagery will be available on film. NOAA soundings are not available in real time.

Similarly, DMSP reception is available for orbits within 1500 n mi, but only selected passes are acquired (hard copy) . The new SSM/I data are expected to be locally received, processed and displayed by the time of the experiment. C. Guard will check whether the microwave temperature profiles will be available.

The GMS high resolution visible and infrared images are available in hard copy. Only the low resolution imagery is presently animated from hourly transmissions. A high resolution digital processing and display system is expected to be installed prior to the field experiment. The GMS operational winds are received in coded format and then are plotted on paper copy.

3) <u>Proposed post-experiment processing</u>

The University of Wisconsin has proposed to:

(i) Collect all NESDIS operational soundings from the NOAA satellite and post-process selected cases (no sounding enhancement);

(ii) Collect all of the DMSP operational soundings and post-process selected cases (no enhancement);

(iii) Collect all GMS operational wind sets and post-process selected cases including enhancement; and

(iv) Produce an atlas and/or video of GMS imagery.

In addition, the University of Wisconsin has been proposed to be the primary satellite data archiving center. The only data that are not expected to be received directly is the high resolution imagery from the DMSP and NOAA polar-orbiting satellites. Ray Zehr is checking with NESDIS about the NOAA imagery. Hardcopy from Guam may be the only archive of the DMSP imagery. The Colorado Snow and Ice Center can provide the DMSP imagery about a year later, but at high cost. The University of Wisconsin should have real time access to the SSM/I data and will archive selected cases. NEPRF is a back-up archive for this data.

4) Outstanding issues and questions

(i) Should a satellite imagery atlas and/or videotape be produced as the University of Wisconsin has proposed?

(ii) Steve Pryor will check the extent to which DMSP imagery may be shared with other countries.

(iii) What is the availability of USSR satellite information?

D. Aircraft

Hugh Willoughby (Chair), Roger Smith, Bill Gray, Michael Douglas, Pavel Sirikunov, Jim McFadden

1) Mission

The primary mission of the aircraft is to augment the rawinsonde network at one synoptic time (00 or 12 UTC) each day during an IOP. A strategy that supports all hypotheses employs one or two aircraft flying box patterns to cover the data-sparse Philippine Sea (Fig. 5a). A single long-range jet aircraft can provide the same coverage (Fig. 5b). When Hypothesis I is the focus of investigation, an alternative is a single aircraft flight track on the poleward side of the TC to map the environmental flow between the TC and the subtropical ridge. When Hypothesis II is the focus, a single aircraft flight track between the TC and the approaching midlatitude trough would map the interactions (Fig. 5c). All of these strategies provide data to improve the estimate of the environmental flow necessary for study of Hypothesis III.

Secondary missions for aircraft might include detailed mapping of the TC core and investigations of mesoscale and convective scale features on the TC's periphery.

2) Possible Aircraft

The WP-3D, operated by NOAA Office of Aircraft Operation, is a four engine, turboprop aircraft with a complete set of flight-level instrumentation, cloud-physics sensors, RHI and PPI meteorological radars, inertial navigation equipment and wind finding (omega) dropwindsondes. In the course of a 9 h mission, it can fly 2700 n mi while attaining a ceiling above 500 hPa early in the flight and above 400 hPa later after it has burned most of the fuel. Participation of one WP-3D depends upon continuing negotiations between the experiment and NOAA.

The WC-130H, operated by the Air Weather Service, is a four-engine turboprop aircraft. Some WC-130H's have the Improved Weather Reconnaissance System modification that provides inertial navigation equipment, automatic data acquisition and digital communication. The unmodified WC-130H's have Doppler navigation, manual data acquisition and voice communications. Both the modified and unmodified versions can be configured to dispense wind finding dropsondes.

The range and ceiling for a nominal 9 h mission are comparable with the WP-3D described above. Participation of two or three WC-130H's depends upon continuing negotiations.

The National Center for Atmospheric Research Electra is also a four-engine turboprop with a ceiling near 350 hPa and a 2400 n mi range. It has inertial navigation equipment, complete flight-level sensor suite, cloud physics instrumentation and digital data acquisition. It can dispense wind-finding dropsondes. The Electra's participation depends upon acceptance of a proposal to the National Science Foundation. If it is part of the experiment, much of its effort will be directed toward observation of mesoscale features.

The NASA DC-8 is a high altitude jet aircraft. During a 9 h mission it can fly 4000 n mi and attain 200 hPa pressure altitude. It has inertial navigation equipment and is a well-equipped research aircraft. It is now configured with neither flight level data nor dropwindsonde systems. Participation of the DC-8 depends upon continuing negotiations and possibly upon availability of supplementary funding. To be useful in the western Pacific field experiment, the DC-8 needs to have flight-level and dropsonde systems installed and proven substantially before the summer of 1990.

The IL-18 and AN-12, which are operated by the Central Aerological Observatory/USSR, are four-engine turboprop aircraft with ranges of less than 2000 n mi and a 400 hPa ceiling. They have Doppler navigation, digital flight-level data systems and cloud physics instrumentation. The IL-18 has PPI and vertical incidence meteorological radars, and the latter is Dopplerized. By the summer of 1990, the aircraft will probably have dropsonde capability for thermodynamic observations only. Although participation of one of these aircraft is considered to be extremely likely, basing for the aircraft is uncertain.

3) Personnel

Each aircraft has a Chief Scientist who flies with the airplane and supervises the scientific crew members. He is responsible for the scientific aspects of assigned missions, for the quality of observations and for coordination with the flight crew. The Aircraft Commander (Pilot) has final authority over actual operation of the aircraft and safety of flight. Each scientific crew member has in-flight responsibility for a particular sensor, such as dropsondes, cloud physics or radar. Dropsonde equipment typically requires two or three crew members if observations are to be transmitted in real time. The aircraft also may carry observers, not normally part of the crew, whose only duty is to watch the weather. Thus, a typical scientific flight crew comprises the Chief Scientist and two to five scientific aircrew or observers.

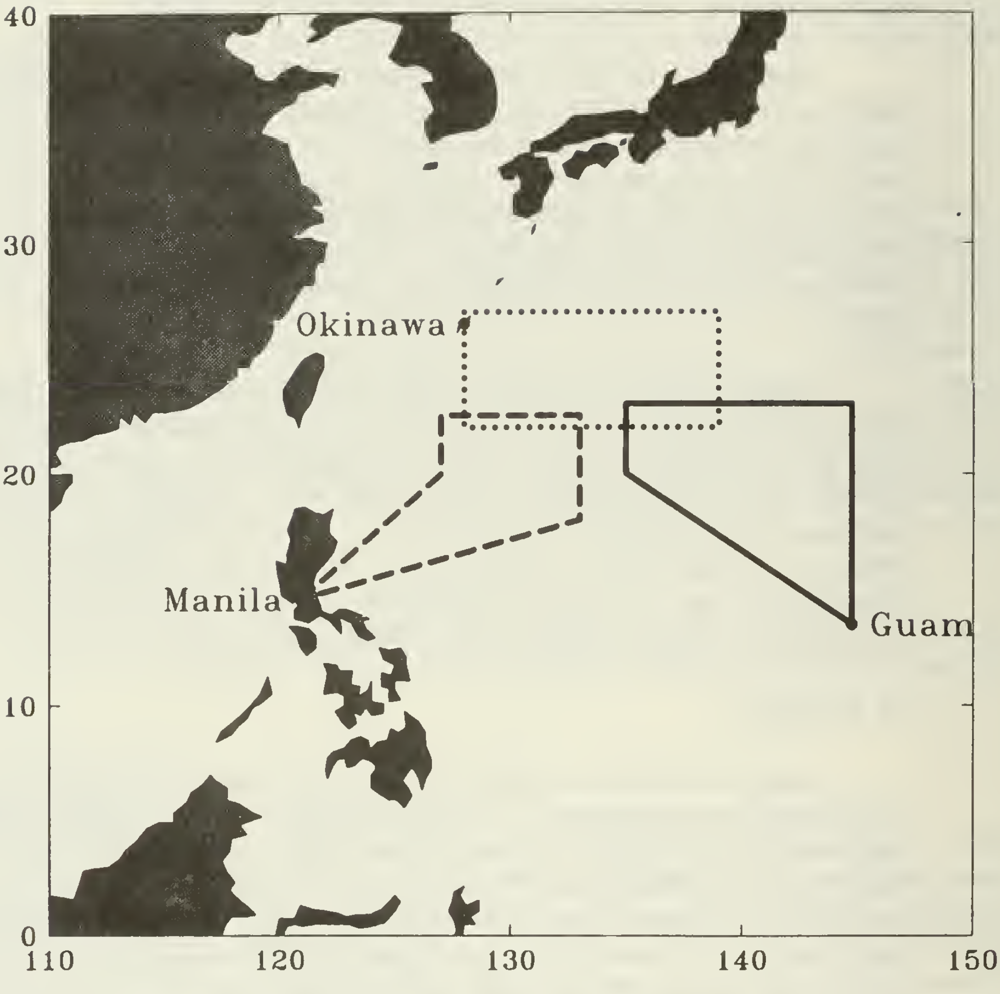


Fig. 5a. Synoptic tracks for turboprop aircraft flights originating from Okinawa, Guam or Manila.

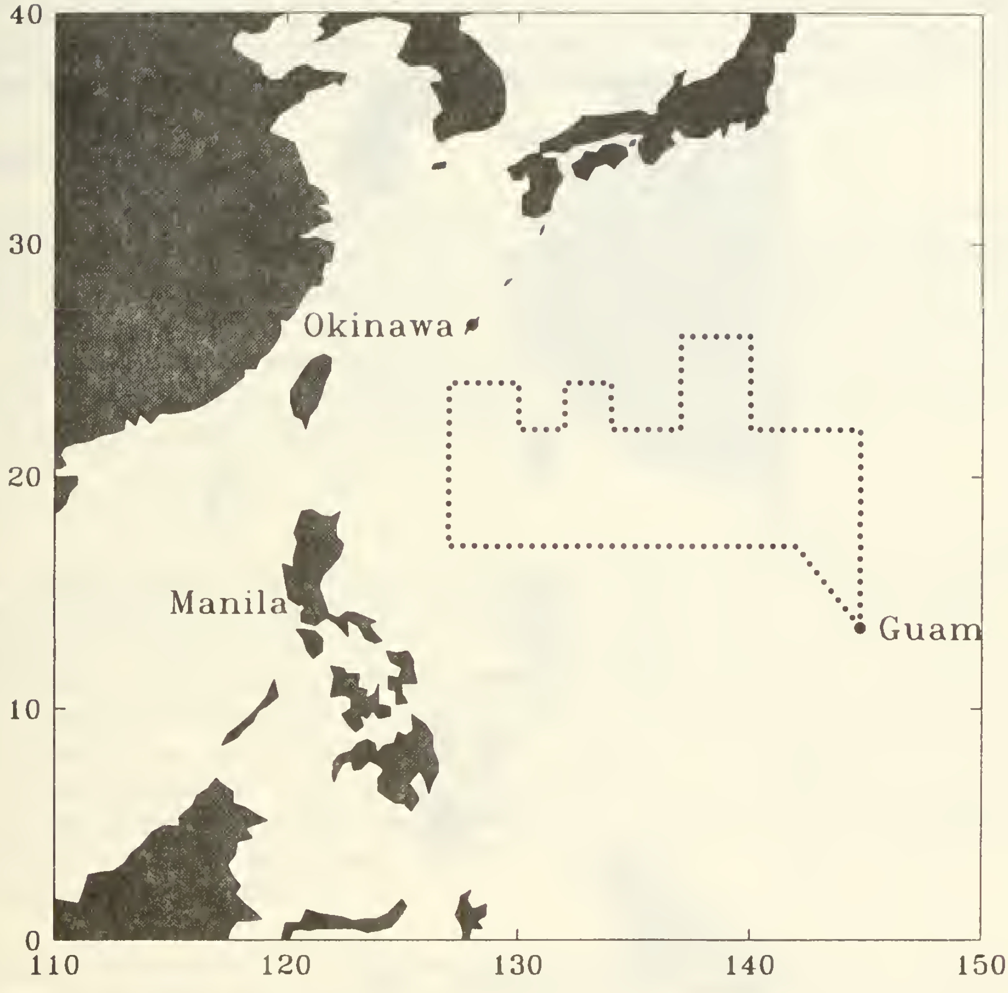


Fig. 5b. As in Fig. 5a, except for a jet aircraft flight originating from Guam.

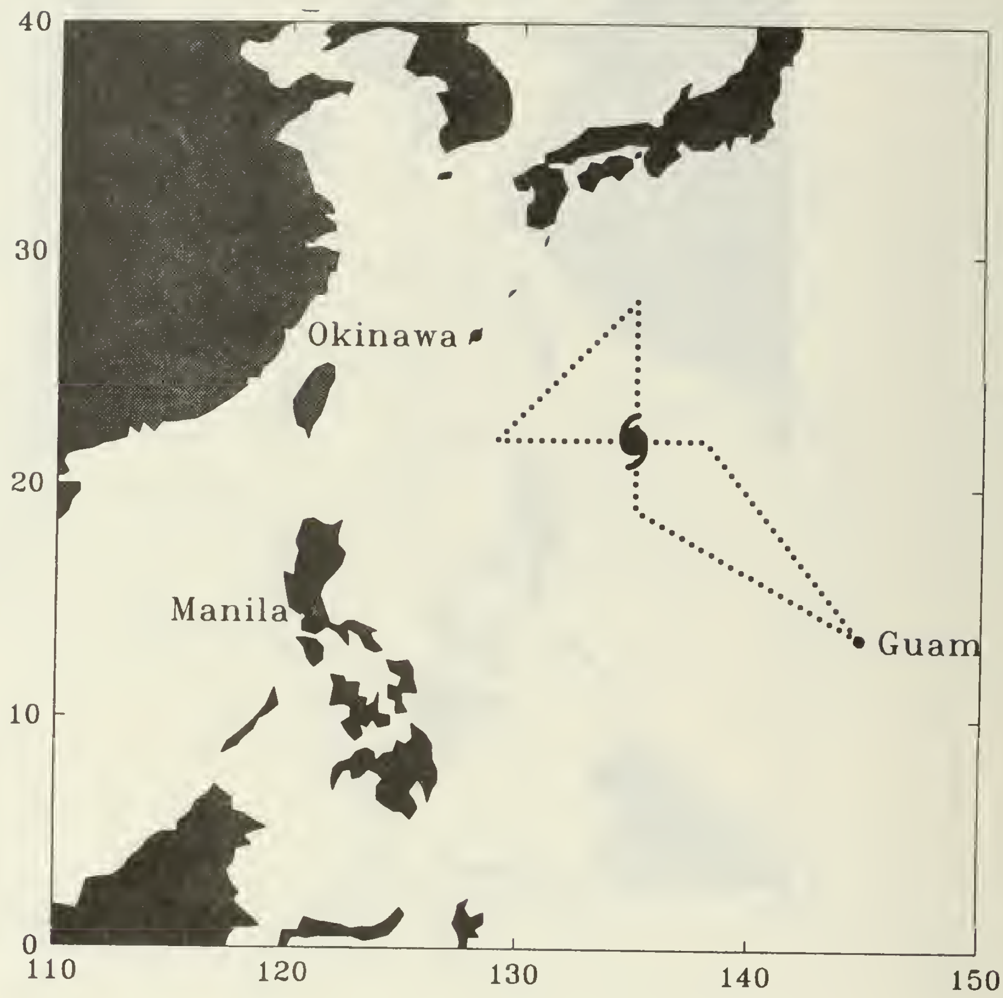


Fig. 5c. Example of an aircraft flight pattern intended to observe the interaction between a tropical cyclone and an adjacent synoptic circulation.

General responsibility for the employment of aircraft resides with the Aircraft Coordinator, who will be one of the Experiment Operations Team in Guam. In conjunction with the Forecast Support Group and Scientific Director, the Aircraft Coordinator will determine mission assignments. The Aircraft Coordinator will brief missions departing from Guam and he will have at least one deputy to brief missions for the aircraft based elsewhere. Normally, neither the Aircraft Coordinator nor the Deputy Aircraft Coordinator will fly.

Total scientific personnel requirements for the aircraft component of the experiment are: Aircraft Coordinator and Deputy Aircraft Coordinator plus an average of five aircraft scientists for each airplane. Thus, if two aircraft participate and use two different bases, we will need 12 people for the duration of the experiment. Only a single flight crew for each aircraft is required to fly the two sorties per aircraft during each IOP.

4) Aircraft Basing

Turboprop aircraft could operate from Anderson AFB on Guam to cover the southeastern corner of the experimental area, from Clark AFB or the Aquino International near Manilla to cover the southwestern corner and from Kadena AFB or Naha Civil Airport on Okinawa to cover the western side. The DC-8 could operate from either Guam or Okinawa. Missions to observe interactions with midlatitude troughs require access to bases in Japan. Logistics are much simpler if aircraft recover at the base where they took off. A number of nonscientific considerations influence basing arrangements.

5) Logistics

The nominal experimental design includes eight IOP's of 48 h maximum duration. Each aircraft can fly one sortie a day, which is assumed to be 9 flight hours Full participation by a single aircraft would be 150 h, which includes time for test and calibration flights, but not ferry time to and from the experimental area. During a single dropsonde mission, one aircraft can typically deploy 20 sondes, so that 32 dropsonde sorties (full participation) by two aircraft would require 640 sondes. If the experiment can accept aircraft observations during only six of the eight IOP opportunities, the resources necessary for full participation by two aircraft can be reduced to a total of 216 flight hours and 480 sondes. Aircraft operations will also require other logistic support such as magnetic tape and office supplies.

One hour of operation for a four-engine turboprop aircraft will cost $2-3K and for the DC-8 more than $5K if the experiment has to pay for it. The USAF and ONR have inventories of 500 Omega and Loran dropwindsondes, respectively, available for the experiment.

All expendables will be prepositioned at the operating bases before the experiment begins. When an aircraft is expected to recover at a different base, it will carry the crew's baggage and expendables for the next mission with it. The ground component of the experiment will arrange for the crew's lodging at the terminus. Organizations operating the aircraft will provide their own aircraft and instrumentation maintenance.

6) Mission Planning

The aircraft's mission should be centered around either 00 or 12 UTC. The 00 UTC alternative is preferred to take advantage of daylight flights. The nominal 9 h mission would depart 4 h before the synoptic time (Fig. 6). For a 00 UTC synoptic time, this would be 20 UTC which is equivalent to 06 Guam time or 04 Manila time. The briefing begins 2 h before takeoff, which is 18 UTC, 04 Guam time or 02 Manila time. The mission would be complete 5 h after the synoptic time (05 UTC, 15 on Guam or 13 in Manila). This schedule allows flight crews 15 h on the ground between missions and 12 h uninterrupted rest between the debrief of one mission and the start of the briefing for the next flight. The intention is to maintain this pace for only two days, which is the duration of an IOP.

Planning for aircraft operations begins the previous day to take advantage of visible satellite imagery and to alert the aircrews. For a mission centered on the 00 UTC synoptic time, the Scientific Director and Aircraft Coordinator, in consultation with the Forecast Support Group, would have selected possible missions to be flown and notified the aircrews on Guam and the Deputy Aircraft Coordinators at the other aircraft bases by 05 UTC on the previous day. As soon as the aircrew awaken (about 17 UTC), they contact the Aircraft Coordinator to determine whether the mission is still scheduled. If it is, they report for briefing and flight planning 2 h before takeoff. If it has been canceled, the Aircraft Coordinator or his Deputy releases them until 05 UTC, which is the normal notification

EVENT	OPTION			
	A	B	C	D
AIRCRAFT CREW PUT ON ALERT	05UT (15GT)	11UT (21GT)	17UT (03GT)	23UT (09GT)
LATEST TIME TO CANCEL MISSION	17UT (03GT)	23UT (09GT)	05UT (15GT)	11UT (21GT)
AIRCRAFT CREW REPORTS	18UT (04GT)	00UT (10GT)	06UT (16GT)	12UT (22GT)
AIRCRAFT TAKEOFF	20UT (06GT)	02UT (12GT)	08UT (18GT)	14UT (00GT)
MISSION CENTER TIME	00UT (15GT)	06UT (21GT)	12UT (03GT)	18UT (09GT)
AIRCRAFT LANDS/DEBRIEF	05UT (15GT)	11UT (21GT)	17UT (03GT)	23UT (09GT)

Fig. 6: Timeline of events related to aircraft operations. Approximately a 9 h flight is assumed with the center time of the flight to coincide with the synoptic times of 00, 06, 12, 18 UTC for Options A-D respectively. The corresponding Guam Time (GT) is given for each event. Subtract one hour from the GT for aircraft based in Okinawa.

time for the next day's flight. For a 12 UTC synoptic time, these times are shifted by 12 h. Changing synoptic times is accomplished only by introduction of a 12 h delay, but this is not done after aircraft operations have commenced.

7) Flight tracks

The following schematic mission designs provide only a basis for actual missions to be flown. They will require modification to fit the situation at hand.

(a) Synoptic tracks. The Guam, Manila and Okinawa synoptic type boxes (Fig. 5a) are dropsonde missions designed to use turboprop aircraft to cover data-sparse areas of the Philippine Sea. The aircraft fly the longest possible track for a 9 h mission at the highest attainable altitude, release dropsondes at half-hour intervals along their track and return to the base from which they took off.

The "Skyline" Track (Fig. 5b) accomplishes the same goal as the box patterns in Fig. 5a, but uses the single DC-8 flying near 200 hPa. Although this mission can use whatever operating base supports the DC-8, Okinawa is the most convenient. As in the box patterns, the goal is to achieve the longest track possible in 9 h, while flying at the highest attainable altitude and releasing dropsondes at 200 - 300 n mi intervals as dictated by ground speed and the sonde rate of fall. The aircraft then returns to the point of departure.

(b) Interaction tracks. The Asymmetric Bow Tie Track in Fig. 5c covers the axis of interaction between the TC and the subtropical ridge or an approaching midlatitude trough. The ideal aircraft for this track is the DC-8 flying at 200 hPa, but turboprop aircraft flying at 500 or 400 hPa may do the mission. The aircraft departs, tracks to the initial point, which in this example is south of the TC. Before the initial point it climbs to the highest attainable (pressure) altitude, which it maintains until it reaches the final point. Between the initial point and final point, the aircraft releases dropwindsondes as rapidly as possible.

(c) Alfa pattern. This figure-4 pattern is a standard track used in operational reconnaissance to map the vortex core. The radial legs typically extend 80 n mi from the center so that an aircraft flies less than 1000 n mi in the course of repeating the pattern twice. The aircraft is at its assigned altitude, usually 850 or 700 hPa when it reaches the initial point and maintains fixed (ideally pressure) altitude throughout the pattern until it reaches the final point. This pattern is simple, easy to fly and covers the vortex well enough to support accurate estimation of the axisymmetric vortex and the wavenumber one asymmetry.

(d) Mesoscale tracks. The Electra missions are designed to focus on the structure of convective bands. The flight tracks appear in the proposal to the NSF for that aircraft's participation.

8) Data quality and format

Before the experiment begins, participating aircraft will conduct a wing-tip to wing-tip intercomparison including a simultaneous dropsonde deployment near a reliable

rawinsonde station. Accuracy of lower-level pressure measurements from the aircraft is a continuing problem because errors magnify through the downward hydrostatic calculation. Each aircraft departing on a dropsonde mission will carry the latest available surface chart and upper air charts below flight level. A hydrostatic computation will be made for every drop and compared with these analyses. Post-flight comparisons will also be made with ground-based soundings during the course of the flight whenever they are sufficiently close in space and time. Finally, each aircraft will conduct a true airspeed calibration every time it flies.

At the end of each flight, the Chief Scientist will submit his completed checklist and hardcopies of observations in the appropriate synoptic code. This is the "quick-look data." Just as Omega dropwindsonde observations require post-processing to improve the wind determination, many other electronically recorded observations need post-processing to incorporate final calibration constants and other corrections evident after the field phase of the experiment. Within 6 months of the end of the experiment, the organization operating the aircraft will provide final magnetic tapes of all observations and FORTRAN-77 callable subroutines to read the tapes.

9. Communications

(a) In-flight. The experimental area is outside the footprint for the USA aircraft-to-satellite communication system. Thus, high-frequency, single sideband voice may be the only communication medium. It will be necessary to make arrangements through JTWC to reactivate an operation similar to the aircraft coordinating office at the National Hurricane Center or the old Swan Monitor for the duration of the experiment. To reduce the volume of H/F traffic, only every second or third dropsonde should be transmitted.

(b) Flight planning. Most of the missions are essentially synoptic tracks. Consequently, telephone communication between the Aircraft Coordinator and the Deputy Aircraft Coordinator or Chief Scientists is adequate, provided that flight planning is carried out with access to current synoptic maps.

E. Doppler radar

Morton Glass (Chair), Ken Glover, Teruo Muramatsu, Cheng-Shang Lee, and A.A. Chernikov

1) Geophysics Laboratory radar

The Geophysics Laboratory (GL) of the US Air Force has funded the Massachusetts Institute of Technology (MIT) to deploy their 5 cm Doppler radar (Table 1) in conjunction with the Tropical Cyclone Motion field experiment. The objective is to acquire Doppler weather radar data sets and supporting *in situ* observations in a variety of tropical storms for the purpose of developing tropical storm observational, tracking and analysis algorithms for real-time use with the Next Generation Weather Radar (NEXRAD). Guam (at Anderson AFB or near the Joint Typhoon Warning Center) and Okinawa (Kadena AFB) have been considered potential sites. Although Okinawa is preferred based on storm frequency climatology, Guam is most likely to be selected for logistical reasons. Obtaining a frequency allocation is a critical first step before any contract work can proceed. Deployment to Okinawa would depend on receipt, within the

next few weeks, of a frequency allocation. Obtaining a frequency allocation is not considered a serious problem at Guam.

A visit to potential sites is considered necessary for selection of the radar location and for making arrangements for site support. Site requirements include:

(i) Cement footings for 15 foot tower.

(ii) Temporary shelter located at distance not to exceed 100 feet from tower.

(iii) Shelter size should be approximately 8 by 30 feet.

(iv) Air conditioning for shelter is mandatory.

(v) A crane is required to erect tower and position radar antenna and radome atop tower.

(vi) Power for radar and for air conditioning of shelter. Radar requires 115v 60Hz 100 amps.

Arrangements for transportation of the MIT radar from Melbourne, Australia, and the radome with support equipment from Massachusetts, will be handled by GL. Although four people will be needed for the installation phase, only two people will be on site during operations.

The GL assumes that Doppler data and supporting data collected by other groups will be shared. GL will prepare a summary of the radar data collected, which will be recorded on 9-track tapes in an MIT-designed format. Copies will be available in this format and will include software for reading these packed tapes. In certain situations, GL will convert tapes to Universal format before transferring the data.

Table 1. Characteristics of the MIT Doppler radar to be installed on Guam or on Okinawa

Type:	Enterprise Doppler
Wavelength:	5 cm
Transmitter Power:	250 kw
Transmitter Pulse Width:	Approx. 1 microsecond
No. of Range Gates:	226 (real-time + archive)
Range (Approximate):	200 km
Antenna Diameter:	8 ft
Beam Width:	1.4 Deg.
Scan Rate:	Variable; 2 RPM for 1 radial/degree
Real Time Displays:	2 Velocity and 2 Reflectivity per volume scan (can not be transmitted)
No. of Scans (PPI's):	Per Volume Scan: 4-20.
Power Requirements:	115 volt, 60 cycle @ 100 amps.

2) Meteorological Research Institute radar

The Japan Meteorological Research Institute (MRI) plans to install a 3 cm Doppler radar (Table 2) on Okinawa provided funds become available. Information as of this date indicate only a 50 percent chance of funds becoming available. Dual Doppler experiments would be possible if both MRI and GL radars are co-located on Okinawa. This type of operation may not be feasible, since close coordination and communication are required for success.

There are 15 conventional (non-Doppler) radar systems in Japan that are capable of storing data in digital form. No information is available on whether data from these systems can be obtained.

Table 2. Characteristics of the MRI Doppler radar that may be installed on Okinawa (Reference: Sakakibara, H., M. Ishibara and Z. Yanagisawa, 1985: Structure of a typhoon rainstorm in the middle latitudes observed by Doppler radar. *Jour. Meteor. Soc. of Japan*, Vol. 63, No. 5)

Wavelength:	3.06 cm
Pulse Length:	1.0 Microseconds
Peak Power:	50 kw
Half-Power Beam Width:	1.0 Deg.
Detectable Min. Signal:	-105 dBm
Pulse Repetition Freq.:	2000Hz
Nyquist Velocity:	15.3 m/sec
Max Range of Process. Doppler Velocity:	64 km
Range Gate width:	250 m

3) National Taiwan University radar

A Doppler radar (Table 3) is operated on the north end of Taiwan under the direction of the Air Navigation and Weather Services. Dr. C.-S. Lee indicates that they are anxious to take part in the program and would be willing to exchange data. He suggests that the simplest means for arranging cooperative agreements is through National Taiwan University.

Five conventional radars are operated in a network around Taiwan. Two of these, at Hwalein and Kaoshiung, record their data digitally. These are 10 cm radars with a range of 500 km and beam width of 2.5 deg. No information is available on the characteristics of the digital tapes or on a mechanism for obtaining the data. If these data can be useful, arrangements probably can be made.

Table 3. Characteristics of the Taiwan Doppler radar

Frequency:	5.61 GHz
PRF:	900/1200 Hz
Pulse Width:	0.5 microseconds
Peak Power:	262 KW
Antenna Az. Rotation Rate:	2 rpm
Antenna Elevation:	- 1 to 90 deg
Dynamic Range:	> 85 dBm
Range Coverage:	120 km
Range Resolution:	1 km
Unambiguous Velocity:	48 m/s
Wind Speed:	6 classes

4) USSR ship radar

A. A. Chernikov of the USSR indicates that it is possible that a 10 cm Doppler radar would be operating aboard one of the ships. If data are collected, A. A. Chernikov indicates that they would be interested in sharing and exchanging data. No information on the characteristics of their radar is available.

F. Surface network

Tom Schroeder (Chair), Ray Partridge

1) Scientific justification

As indicated in Elsberry (1988b), the justifications for the surface network are:

(i) Provide additional data in the middle of the Philippine Sea. Since the USSR vessels must resupply at regular intervals, there will be periods of up to seven days when the central Philippine Sea will be a data-void region.

(ii) Provide ground truth for satellite sounders.

2) Ships of opportunity

T. Schroeder has reanalyzed the Comprehensive Ocean Atmosphere Data Set (COADS) using August and September 1979 as a standard for comparison. The intensive data collection effort during the ESCAP/WMO Typhoon Committee experiment should yield about the same ship reporting frequency as in 1979. Approximately 40 ship reports were recovered in the standard 6 h reporting time, which is double the earlier estimate. Daytime reports constituted 60 percent of the sample. During 1979, an additional 40 ship reports per day were recovered for non-standard observation times. The area examined was limited to the Philippine Sea so the many additional reports that are available in the South China Sea are not included in these totals.

Cooperation with the Typhoon Committee experiment is important since the Typhoon Committee Members (especially Hong Kong) already have special ship of opportunity reporting programs during typhoons. It is recommended that the Experiment Director request that these Asian nations activate their ship reporting programs.

3) Island station enhancements

Installation of automatic surface stations within the US affiliated territories is proceeding in a timely fashion. Pagan Island in the Northern Marianas is scheduled for installation prior to 1 October 1989. Farallon De Pajaros is scheduled for a station well before the beginning of the experiment. Farallon Island is a volcanic cone and exposure of wind sensors could be affected.

4) Drifting buoys

Because of the high cost of large drifting buoys, the working group recommended that only mini-drifter buoys be considered. An inexpensive (about $2,200) mini-drifter was tested successfully during the ERICA field program in the Atlantic. Since mini-drifters are deployable through sonobuoy chutes, any operational P-3 could easily deploy them as part of a training mission. The other advantage is that more than one deployment could be made during the two months.

Even though the mini-drifters have no wind instruments, sufficient justifications exist to deploy them during 1990. A lattice of buoys at 5 deg. lat. separation between 15 and 25° N and 140 and 130° W requires only 9 drifters, and two deployments would require 18 buoys. If a second deployment is not required, the buoys would be available for seeding across the path of an approaching storm or some other special mission.

5) Costs

Island station enhancement and ship-of-opportunity recovery should be handled within other programs (e.g., the Navy/National Weather Service Micronesian station enhancement and Tropical Ocean Global Atmosphere). One person is needed at Guam to monitor the data flow and collect all special surface observations. The overall cost of the surface network enhancement should be less than $100K.

G. Experiment forecast support

Greg Holland (Chair), Melinda Peng (Rapporteur), Masanori Yamasaki, Mark Lander, Colin Ramage, Chip Guard, Teruo Muramatsu, Les Carr, Sung-kyu Kim, Yoshio Kurihara

1) Requirement

The forecast support group will provide specialized forecasts for use in planning, operational deployments, and warnings of typhoon conditions at experiment sites. The opportunity also will be taken to examine current forecast methods and to consider potential improvements.

2. Site

Experiment forecasters will be located within the Joint Typhoon Warning Center (JTWC), Guam. The proposed procedure is to have 2-4 experiment forecasters supplement the routine forecast cycle at JTWC and to make forecast decisions in collaboration with JTWC forecasters. This will make maximum use of the available JTWC products and expertise. JTWC also will benefit from the interactions with the experiment forecasters, all of whom have many years experience, and from the testing and implementation of new techniques for the experiment.

3. Forecasters

Dr. G. J. Holland will lead the experiment forecast team and will coordinate their activities with the Director of JTWC, Lt. Col. C.H.P. Guard. A forecast team consisting of Dr. C. Ramage, Dr. R.T. Merrill and Mr. M. Lander has been selected, subject to confirmation by JTWC and the Experiment Director. This number of forecasters will only be needed for the period of aircraft operations. Two duty forecasters will be sufficient during the remainder of the period.

4) Operational schedule

The entire North Pacific west of the dateline will be monitored throughout the experiment. Specific forecasts will be made for the region west of 150° E and north of the equator. Three operational phases are planned:

(a) Standby phase. When no storms are forecast within the experimental region within 48 h, the forecast team will operate in standby mode. A 24 h duty roster is planned, with the following schedule (all times are Guam LST):

0600-0830 Situation evaluation and attendance at JTWC brief

0830-1700 On call, re-evaluate situation as required;

1600-1800 Re-evaluate situation, brief the Experiment Director and Principal Investigators at 1700;

1900-0600 On call.

(b) Planning phase. If a storm is expected within the experiment domain within 48 h, the Experiment Director will be briefed and the roster will change to:

0600-1800 On duty at JTWC, attend JTWC briefs, brief Experiment Director and Principal Investigators at 0930 and 1700;

1900-0600 On call.

(c) Operations phase. When aircraft operations are planned, the forecast roster will be supplemented by an additional forecaster whose sole responsibility will be to provide forecasting briefs for the aircraft operations.

A set of beepers will need to be obtained to allow ready access to the duty forecaster when he is not in JTWC. It also is highly desirable that all forecasters be located in the Nimitz Hill BOQ to allow immediate access to JTWC.

A routine evaluation of the forecast effort is to be carried out following each typhoon. This will be facilitated by diaries that will be maintained at the forecast counter where each forecaster can record the forecast reasoning. These evaluations will be summarized in a post-experiment report. The seasonal summary will follow the form of the *Annual Tropical Cyclone Report*, but with input from both JTWC and experiment forecasters.

A check-sheet describing the detailed daily requirements at the forecast center is to be developed. This will include a list of all experiment resources and personnel at risk, together with the means of communication. Holland and Lander are responsible for developing the check sheets and roster cycles, and for arranging operational logistics within JTWC.

5) Forecast dissemination

Three types of forecasts are planned: general briefings; mission briefings; and warnings. The general briefings shall be conducted at regular times each day and will consist of a general overview of the current situation, specific weather forecasts for Guam, and specific forecasts of typhoons as required by the Experiment director and Principal Investigators. Mission briefings will be specifically tailored to aircraft mission requirements with a detailed brief to the aircrew and mission scientists. All experiment facilities at risk, together with those of collaborating experiments, will be provided with advice and warnings of the likelihood of typhoon conditions. The type of advice will be tailored to fit the items required for securing equipment, evacuation of personnel, etc. Holland, Lander and Guard will prepare a summary of experimental resources at risk and make arrangements for forecast dissemination.

6) Briefing room

Security and space considerations prevent routine access to the JTWC forecast spaces by a large group of experimenters. Thus, only the experiment forecaster and Director will have direct access. A briefing room will be needed for forecast briefings, for general discussions and for some forecasting laboratories that are planned. This room should be large enough to accommodate 10-20 people standing and 5-6 people working, should have space for hanging charts, and should have an overhead transparency projector. An Automated Tropical Cyclone Forecast (ATCF) terminal would be very desirable. McMorrow, Guard and Holland will investigate these aspects.

7) Support techniques and equipment

The routinely available techniques and equipment at JTWC will provide the major forecast support. By the time of the experiment, these are expected to include the ATCF workstations, a satellite workstation, access to all FNOC numerical products, locally hand-drawn analyses, ECMWF and NMC extended range forecasts and a number of statistical and empirical methods. The ATCF workstations provide ready access to most of these

products and one Z248 computer will need to be allocated as a workstation for the exclusive use of the experiment forecast team.

A number of additional forecast diagnostics are being prepared for the experiment: a synoptic history of a number of previous typhoons for pre-experiment "training" of the forecasters; a check sheet for operations and to support the forecast decision making process; an angular momentum budget program for structure change forecasts; and a regular tracking of synoptic features, such as TUTT cells. Additional potential techniques are being investigated.

Lander and Holland, together with Martin and Wells at JTWC, are to investigate the above aspects.

8) Data

The highest priority should be given to ensuring that all routinely available experimental data are collected at JTWC to support the forecast process. Data collection processes are described under data management. All GTS data should be received at FNOC and utilized in the numerical analyses that are forwarded to JTWC. Additional data received only at JTWC are routinely incorporated in the hand analyses. These data also will be manually added to the ATCF data base for reanalysis with the Barnes analysis scheme.

Significant communication problems must be solved to arrange for experimental data to be transmitted in real-time to JTWC. For example, profiler data may come via HF, telephone dial-up or satellite link. An early consideration of these problems by the experiment data manager is recommended.

The data gathered in the complementary experiments by the Typhoon Committee countries, by the USSR and by Taiwan are expected to be available in real time via the GTS. Radar fixes from the MIT radar on Guam and other radars will be obtained by telephone discussion with the on-site personnel. Aircraft dropsonde data, together with in-flight weather observations, are expected to be transmitted by HF radio.

Some local archiving of data that come solely to Guam is needed. Guard and Lander will investigate this following the appointment of a data manager.

9) Concomitant forecast experiment

The presence of so many experienced tropical meteorologist at Guam for the experiment provides an excellent opportunity to evaluate a number of forecast techniques and methodologies from the forecaster perspective, to develop new procedures, and to see if quantitative forecast improvements result. Plans for this aspect will be developed in collaboration with the JTWC Director and forecasters. Merrill, Ramage and Holland will investigate further.

10) Consultation with other experiments

The USSR forecast center will be on their flagship. This will include numerical analyses, numerical forecasts of typhoon motion, and forecasts of tropical storm development. It seems likely that the Typhoon Committee forecasts will be issued from the Regional Specialized Meteorological Center (RSMC) in Japan. The Taiwan issue forecasts will be issued by the Central Weather Bureau in Taipei.

Some reliable communication between these experiment forecast centers needs to be established. A regular daily discussion schedule would be preferred. Holland and Elsberry will investigate further.

11) Pre-experiment forecast test

An evaluation of the planned forecast center will be conducted from late August and early September 1989. Lander will be at JTWC for the test period and Holland plans to visit for approximately one week. The forecast team will make individual forecasts and communicate by telemail. The experience gained will be used in preparation for the 1990 experiment. A similar "lead up" phase for the experiment is planned for the last two weeks in July 1990.

H. Data management

Ted Tsui (Chair), Jenni Evans, Jan-Hwa Chu, Lance Leslie, Steve Lord and Bin Wang

1) Introduction

The primary responsibility of the data management in the Tropical Cyclone Motion Experiment is to establish workable procedures to:

(i) collect all available real-time data during the field experiment and non-transmitted data that become available within three months after the experiment;

(ii) collate the collected data for distribution;

(iii) assimilate the collated data for data analysis, and

(iv) act as the post-experiment data analysis distribution center.

It is recommended that a Field Experiment Data Integration Center (FEDIC) be established as a focal point for integrated data dissemination and a Post-Experimental Analysis Center (PEAC) be established to carry out post-experiment data analysis (Fig. 7). The FEDIC personnel will be located at JTWC during the field experiment. It is proposed that the FEDIC be situated in a "cooperating facility" where data from the Global Telecommunications Systems are routinely extracted and processed. The PEAC does not have to be co-located with the FEDIC. However, the PEAC ideally should also be situated in a "cooperating facility" where tropical cyclone analyses are routinely generated.

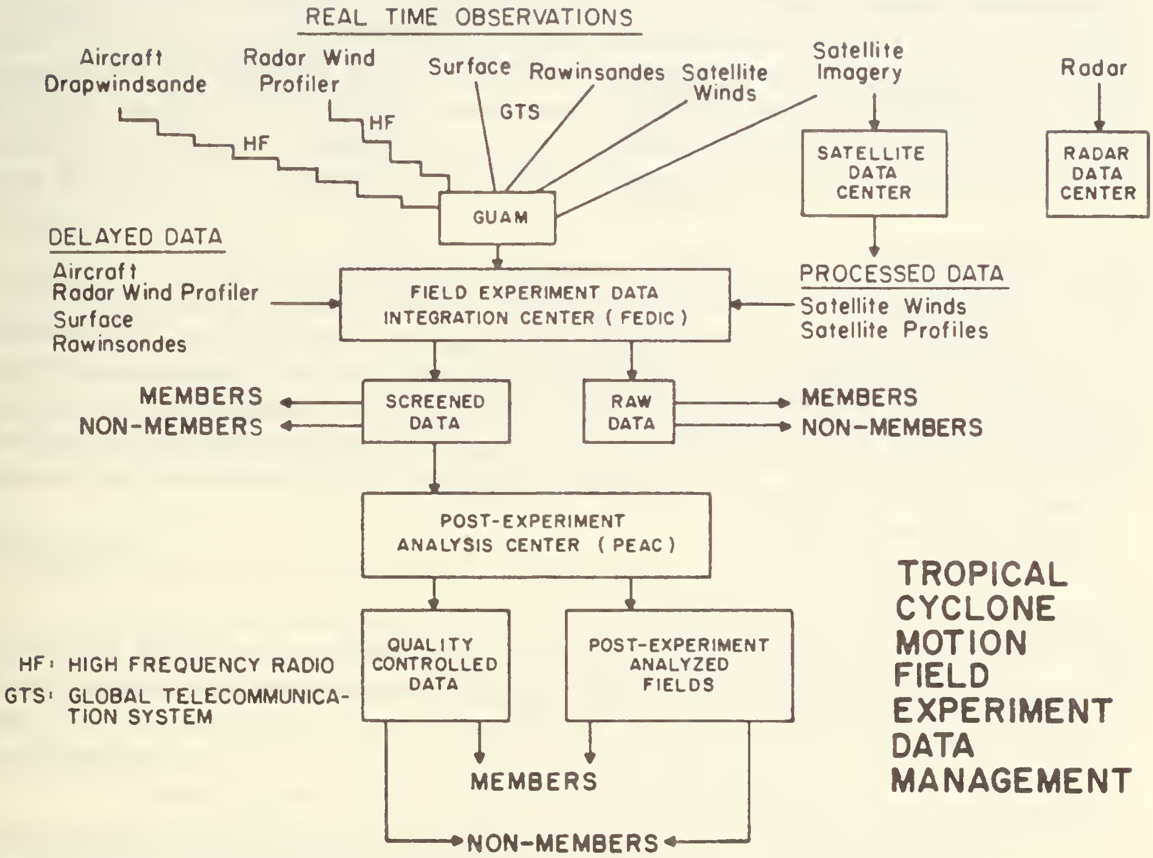


Fig. 7. Data flow from the tropical cyclone motion field experiment (see text for explanation).

Four major types of data will be collected in the field experiment: Conventional data; Experimental data, Image Atlas and Data Catalog. The conventional data include all types of data currently being used operationally to produce the global and regional model analyses. The experimental data include all types of data available only to the experiment. The Image Atlas may include both radar and satellite image sequences. The Data Catalog will be produced by FEDIC. Each of these types will be discussed below.

2) Conventional data

(a) Satellite. Satellite data include digital data from the geostationary GMS and polar orbiting NOAA and DMSP satellites. The University of Wisconsin has been proposed as the satellite data center. The table below shows the satellite data availability.

	GMS	NOAA	DMSP
Availability	Hourly	2/day/satellite	2/day/satellite
VIS	IMAGER	AVHRR	OLS
IR	IMAGER	AVHRR	OLS
Microwave	N/A	N/A	SSM/I
Soundings	N/A	TOVS	SSM/T

Both TOVS and SSM/T soundings generated by NESDIS should be available to the experiment through GTS. In the post-experiment mode, the University of Wisconsin has proposed some post-processing of both TOVS and SSM/T soundings using the simultaneous physical retrieval algorithm. Only slight differences are expected between these two types of retrievals. The SSM/I images from DMSP will also be collected by the University of Wisconsin.

(b) Radar. All radar data will be collected by the individual sponsors of the equipment.

(c) GTS. The data available on the Global Telecommunications System (GTS) are the conventional surface observations, upper-air observations, ship reports, and satellite winds. During the experiment, the FEDIC will move to JTWC and the GTS data will be collected by the "cooperating facility." Needless to say, the arrangements for this data collection must be made well prior to the beginning of the experiment.

(d) Model output. The global (NOGAPS) and regional (NORAPS) model outputs are routinely generated by FNOC and transmitted to JTWC. However, these fields are not in the digital format of the standard Navy communication system. Digital data of NOGAPS can only be obtained by JTWC through the ATCF system and the Navy/NOAA Oceanographic Data Distribution System. However, these fields are transmitted through the regular commercial telephone line. Arrangements must be made before the experiment if a large number of forecast fields constructed from NOGAPS are to be made available to the ATCF system.

3) Experimental data

(a) Wind profiler. All radar wind profiler data will be collected by the individual sponsors of the equipment. However, the real-time vertical wind profiles transmitted to JTWC will be collected by FEDIC.

(b) Aircraft. All aircraft data including dropsonde data will be collected by the individual sponsors of the equipment. However, the wind reports and center fixes sent to JTWC will be collected by FEDIC.

(c) Buoy. Data from the drifting buoys are transmitted to JTWC and will be collected by FEDIC.

(d) Tropical cyclone. Tropical cyclone data include the position fixes, best track positions, warning information, tropical cyclone objective aid data, and post-storm error statistics produced by both the Experiment Forecast Team and JTWC. All these data sets are available through the ATCF data management system. The FEDIC will be responsible for collecting these data. In addition to the digital data, the charts, satellite pictures and messages available to the Experiment Forecast Team during the experiment will be collected and catalogued by FEDIC.

(e) Other experiments. Data fields generated by the other cooperating experiments that will be simultaneously held with the Tropical Cyclone Motion field experiment will be available through the GTS. However, some special data sets may be available only in the post-experiment mode. These data will be coordinated and obtained by FEDIC. In addition to the routine ship observations available from the GTS, many U.S. Navy ship observations will become available three months later as they are declassified. The FEDIC will make arrangements with FNOC to obtain these data.

4) Image Atlas

The University of Wisconsin has proposed a GMS Image Atlas during the field experiment. A video tape may also be made available. The Geophysics Laboratory of the Air Force is expected to produce a radar image atlas from the radar installation on Guam.

5) Data Catalog

After the experiment, a data catalog will be prepared. The FEDIC will be responsible for the distribution of the publication.

6) Data processing

All real-time data reaching JTWC will be collected by the FEDIC. Most of these data will have been saved by either sponsors of the observing platforms or the "cooperating facility" mentioned above. This duplicating effort is not wasteful because it also fulfills the data collection back-up function.

Two types of real-time data will be available: the Intensive Observing Periods (IOP's); and the Non-Intensive Observing Periods (Non-IOP's). All data types will be available during the IOP's. For example, upper-air soundings will be made four times a day. During the Non-IOP's, upper-air sounding s will be available twice a day. Priority levels will be assigned to each IOP and Non-IOP to determine the order for processing the data sets.

The University of Hawaii has proposed that a handanalysis be prepared for the IOP's. A "quick-look" analysis will be produced at many operational centers based on the data transmitted on the GTS. The following discussion is related to production of a more complete, dynamically-consistent set of analyses from the field experiment data set.

Not all data sets will be sent to the FEDIC, because only the data sets needed for producing the post-experiment analyses are required at the FEDIC. However, the description of all data types should be sent to the center for producing a Data Catalog. The Data Catalog will contain all names and addresses of the sponsors of the observing platforms so that the interested individuals can write to the sponsors for the special data sets.

All data sets described below include the description of the data sets or the reading instructions.

Raw Data are data in the form received by the FEDIC after the experiment from the sponsors of the observing platforms and the "cooperating facility." Raw data also will include the data obtained from the cooperating experiments.

Screened Data are raw data that have been converted to a prescribed format that can be read by all participants of the experiment. In addition, screened data should contain neither transmission glitches nor illogical data. The screened data are sent to the PEAC for producing the post-experiment analysis set.

Quality Controlled Data are screened data with the quality control flags added. In other words, after the screened data have been analyzed via the data assimilation cycle, the resultant data are the Quality Controlled Data.

Post-Experiment Analyses are the analyses produced by PEAC's data assimilation scheme from the Screened Data. During the data assimilation cycle, the analysis scheme employed at the PEAC shall add the quality control flags to the Screened Data to form Quality Controlled Data.

The Post-Experiment Analysis shall cover the area bounded by 100° E and 160° E, Equator and 45° N. The grid point spacing shall be between 50 and 100 km. The PEAC shall produce 15 levels of analysis including a surface level and a 1000 mb level. Four

analyses a day will be available for the IOP's and two analyses a day for the Non-IOP's. Atmospheric variables include in the analysis set will be Surface Pressure, Wind, Temperature, and Relative Humidity. A special data set describing the surface characteristics (e.g., terrain height, roughness, etc.) will be made available.

7) Data distribution

All participants of the experiment are classified as "members." Also classified as members are the "cooperating facility" and the members of cooperating experiments. All other parties who wish to obtain data are classified as "non-members."

Fees covering the data handling and tape/disk cost will be charged to each data requester. Administrative fees may also be charged to non-members.

All written reports will be made available in 8.5" x 11" format. All digital data will be distributed via 1600 BPI 9 track tape.

The Image Atlas will be made available in the photocopy format. As indicated above, a satellite video tape may also be available.

The Data Catalog will be made available on 5.25" floppy disk in 260K IBM ASCII format.

The table below is the tentative schedule (number of months) for making the various data sets available.

	FEDIC/ PEAC	Members	Non-Members
Raw Data	3	6	12
Data Catalog	5	6	12
Screened Data	5	6	12
Quality Controlled Data	11	12	24
Post-Experiment Analysis	11	12	24

8) FEDIC Personnel

Two two-year full-time positions are recommended to be created as soon as possible. The Data Manager position should be at the "cooperating facility" where GTS data can be accessed and data tapes can be made available. The position should be filled at the beginning of 1990, since the manager must establish the procedure for data extraction and format conversion for the experiment. The qualifications for the position should include extensive experience in environmental data processing. Experience in environmental field experiments is highly desired.

The Data Assistant position might be divided into a Data Assistant and a clerk. For the efficiency of the task, it recommended that a two-year full-time data assistant position be created. This assistant will be alternating shifts with the manager during the experiment and will assist the manager in the area of data distribution and correspondence. The position should be filled at the beginning of 1990, since the correspondence of the experiment with the data center should peak before the experiment. The qualifications for this position should include some FORTRAN and data conversion experience.

9) PEAC personnel

A two-year, full-time Data Analysis Specialist position should be created as soon as possible. This senior scientist will need to resolve many analysis issues (see below). The analyst must have previous tropical analysis experience, particularly in the cyclone bogusing area.

An estimate for the cost of data management is very difficult to make. The cost for establishing the FEDIC and the PEAC will depend upon the degree to which the cooperating facility will absorb some of the costs. For example, it is highly probable that one of the positions will be absorbed by the cooperating facility. In addition, computer costs are assumed to be absorbed by the cooperating facility.

Four cooperating facilities could become either the data center or the analysis center. These are the Bureau of Meteorological Research Center (BMRC), Melbourne, Australia; Naval Environmental Prediction Research Facility (NEPRF), Monterey, CA; National Meteorological Center, Washington, D.C.; and University of Wisconsin, Madison, WI.

10) Issues and concerns

There are four major areas of concern that the data management working group could not resolve:

(i) Analysis Approach: Since the potential analysis centers have different analysis schemes, it is very important to reach a decision regarding the best analysis approach. For example, should the center produce the analyses with the bogused topical cyclone center? If the answer is yes, then the method to bogus the storm center should be fully discussed.

In the selection of the PEAC, one consequential factor must be considered. Since any adjustments to the current analysis approach at the selected center would induce large costs, it is recommended that the selection of the PEAC implies the adoption of the PEAC analysis approach.

(ii) SST Analysis: Should a sea-surface temperature analysis be produced? If the answer is yes, then how?

(iii) Real-time Transmission: The method for JTWC to receive all observed data has not been resolved.

(iv) Foreign National Data Exchange: If NEPRF becomes the data center, a formal agreement must be obtained in order for NEPRF to exchange data with foreign agencies.

I. Experiment Operations

No working group was formed to discuss the Experiment Operations Center. Although this omission was partly due to the limited time available, this topic needs to discussed as a committee-of-the-whole. The schedule of operations will include a series of briefings: Experiment forecasts; Status reports on observational systems; Status report on expended/remaining resources; Status report of experimental goals achieved or needed to be addressed, etc.

The primary decision of the Operations Center will be initiating and terminating an Intensive Observing Period (IOP) to address a specific hypothesis (see Section 2). Each such IOP will be recapped for assessing the success and for lessons learned. Another activity will involve trouble shooting of observational systems, communication problems, etc. Finally, coordination with the other cooperating experiments will be beneficial to achieve the optimum data sets for tropical cyclone studies.

The Experiment Director will be R. L. Elsberry, who will have the final responsibility for decisions. The Director will seek the advice of three groups. First, the scientific participants present during the field experiment will discuss the situation and offer advice for action. Second, observational system representatives such as the Aircraft Coordinator will provide input from their perspective. Other coordinators might represent the Upper Air (including ships), radar wind profilers, etc. Third, international representatives might be present or be polled by telephone.

As indicated in the experiment forecast support discussions (Section 3G), more cases have to be examined to focus the forecast decision. Robert Merrill posed the forecast problem in terms of two questions:

(i) Will a TC interaction event with either a subtropical ridge or TUTT cell (Fig. 8a) or a midlatitude trough (Fig. 8b) occur with an onset in 24 h and an end by 72 h?

(ii) Will the event occur in the proper location so that the observational network is adequate to test a specific hypothesis? Thus, a list of conditions under which an IOP would be called to investigate a specific hypothesis is required. For example, what relative positions of the TC and the subtropical ridge would trigger an IOP to test Hypothesis I? Will only typhoon strength systems be studied, or will tropical storms also be eligible? Should the 48-h IOP include the verification period of the prediction models as well as the physical process calculations of the diagnostic studies?

Additional discussion is also necessary regarding the relative mix of cases addressing Hypotheses I - III (or the newly proposed hypothesis) that should be sought. Is it likely that both Hypothesis I and II could be studied at different stages in the life cycle of a single typhoon? How much "down-time" between two IOP's would be required? If resources have been expended for two TUTT cases early in the field experiment, should a similar TUTT case be passed up to wait for a midlatitude case? These issues are heightened if the aircraft will be present for only a portion of the experiment.

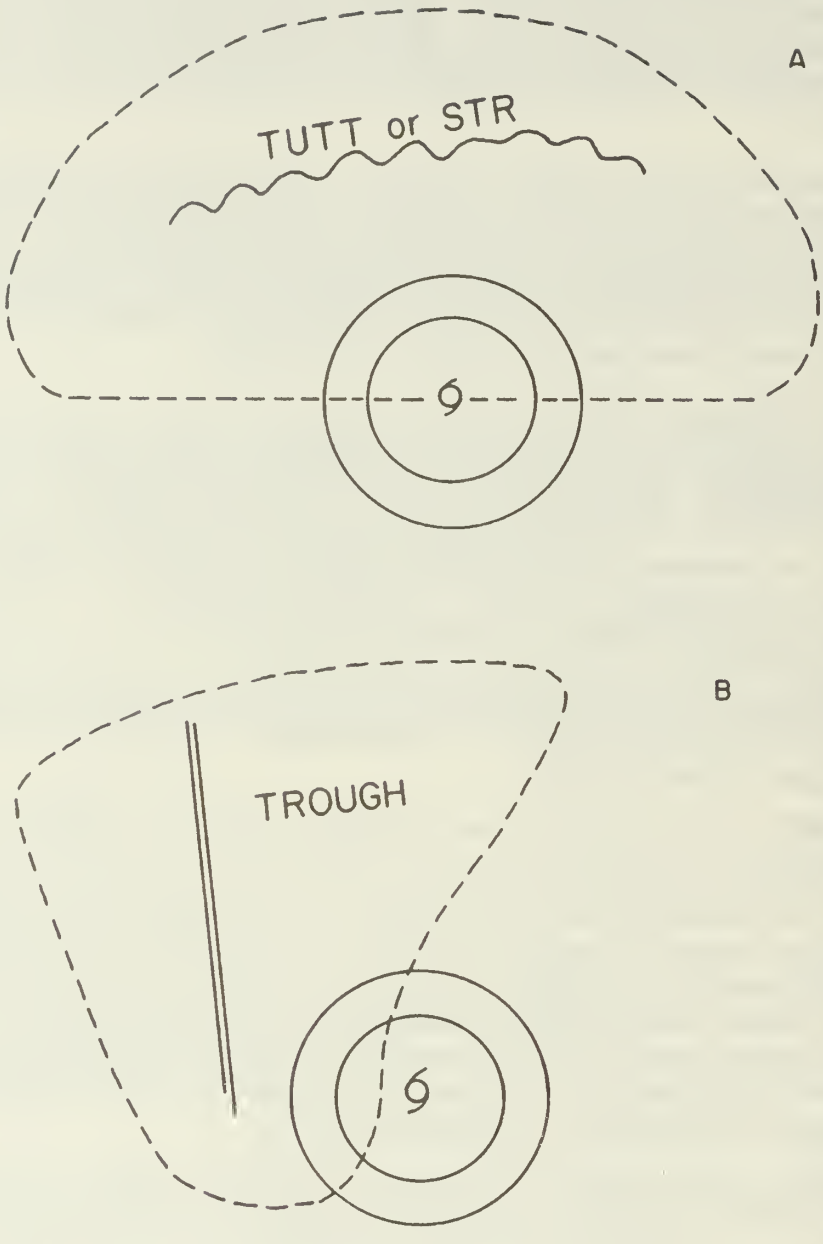


Fig. 8. Schematic illustration of the problem of attempting to forecast the relative positions of a tropical cyclone and the (a) Tropical Upper Tropospheric Trough (TUTT) or Subtropical Ridge (STR) or (b) midlatitude trough as required to initiate an Intensive Observation Period.

Coordination with the other experiments also raises some issues. If the timing of an IOP will conflict with the objectives of another experiment, should the IOP be shortened? How close to land should a TC be when the IOP should be cancelled?

Many of these issues can be left to future workshops when the observational network and special platforms are well known. Additional discussion of the hypotheses and their relative priorities are also necessary. Finally, coordination with the other field experiments is also required.

4. Schedule

The above working group discussions provide the basis for preparing the first draft of a Field Experiment Plan. The tentative date for this draft is September 1989.

A small workshop to address the objective analysis and data assimilation of the field experiment observations will be held in Monterey, California on 31 August - 1 September 1989. This workshop should provide a basis for selecting a group to prepare the final analysis for the field experiment.

A pre-experiment testing of forecast procedures is planned for late August and early September 1989 (see Section 3G). Procedures for calling an IOP can be developed based on this pre-experiment test.

The next workshop is scheduled in conjunction with the Second International Workshop on Tropical Cyclones to be held in Manila, RP beginning on 27 November 1989. Further coordination with the other cooperating experiments is expected at that workshop. This will provide the basis for final adjustments to the Field Experiment Plan, which should then be published in early 1990.

The target date for operation of the radar wind profilers is 1 July 1990. The forecast team is expected to begin operating around 25 July 1990. Other observational systems and communication facilities should be tested prior to the beginning of the experiment on 1 August 1990.

Acknowledgements

The working group reports by W. Frank, C. Velden and J. C.-L. Chan, T. Schroeder, H. Willoughby, M. Glass, T. Tsui and G. Holland are the important contributions to this report research plans. Preparation of the workshop report has been supported by the Naval Postgraduate School direct research funding. G. Holland reviewed this manuscript which was skillfully prepared by Ms. J. Murray.

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APPENDIX A

LIST OF ATTENDEES

Observers

Teruo Muramatsu	ESCAP/WMO Typhoon Committee
Ellaquim Adug	ESCAP/WMO Typhoon Committee
Sung-Kyu Kim	Korean Meteorological Service
Johnny Chan	Hong Kong
Cheng-Sheng Lee	Taiwan
Albert Chernikov	USSR Central Aerological Observatory
Pavel Svizkounov	USSR Institute of Experimental Meteorology
Igor Sitnikov	USSR Hydrometeorological Research Center

Participants

Chip Guard	Joint Typhoon Warning Center
Greg Holland	Bureau of Meteorology Research Center
Melinda Peng	Naval Postgraduate School
Misuzu Wada	Meteorological Research Institute
Masanori Yamasaki	Meteorological Research Institute
Les Carr	Naval Postgraduate School
Colin Ramage	Cooperative Institute Research Environmental Sciences
Michael Douglas	Cooperative Institute Research Environmental Sciences
Mark Lander	University of Hawaii
Wayne Schubert	Colorado State University
Joseph Chi	University of District of Columbia
Chris Velden	University of Wisconsin
Stephen Pryor	First Weather Wing
Dan McMorrow	Joint Typhoon Warning Center
Morton Glass	Geophysical Laboratory
Kenneth Glover	Geophysical Laboratory
Russ Elsberry	Naval Postgraduate School
Tom Schroeder	University of Hawaii
Bin Wang	University of Hawaii
Bill Frank	Penn State University
Bill Gray	Colorado State University
Ray Partridge	Naval Oceanography Command
Jim Countryman	Yale University
Robert Merrill	University of Wisconsin
Robert Abbey	Office of Naval Research
Kenneth Gage	Aeronomy Lab - NOAA
Werner Eklund	Aeronomy Lab - NOAA
Wolfgang Ulrich	University of Munich

Roger Smith	University of Munich
Yoshio Kurihara	Geophysical Fluid Dynamics Lab
James McFadden	Office of Aircraft Operations - NOAA
Hugh Willoughby	Hurricane Research Division - NOAA
Michael Reeder	University of Munich
T. N. Krishnamurti	Florida State University
Duane Stevens	Colorado State University
Charles Holliday	Air Force Global Weather Center
Ray Zehr	NOAA/NESDIS/CSU
Lance Leslie	Bureau of Meteorology Research Center
Graeme Hubbert	Bureau of Meteorology Research Center
Stephen Lord	National Meteorological Center
Jan-Hwa Chu	Naval Environmental Prediction Research Facility
Ted Tsui	Naval Environmental Prediction Research Facility
Bruce Morton	Monash University
Jenni Evans	Monash University
Stephen Hodanish	Colorado State University
Chris Landsea	Colorado State University
Naomi Surgi	University of Miami
Lloyd Shapiro	Hurricane Research Division - NOAA

APPENDIX B

FIELD EXPERIMENT PLANNING WORKSHOP
San Diego, California

AGENDA

Friday 19 May 1989

1300 Registration/Introduction
1305 Workshop Objectives -- Russ Elsberry
1310 ONR Status Report -- Bob Abbey
1315 Synoptic background: Case Study -- University of Hawaii
1330 Discussion of Hypothesis I
    Russ Elsberry, Discussion Leader
1400 Discussion of Hypothesis II
    Greg Holland -- Discussion leader
1500 Break
1515 Discussion of Hypothesis III
1545 Introduction of new hypotheses
1600 Working group organization meetings

Saturday 20 May 1989

0830 Working Group meetings
1000 Working group reports
    Radar wind profiler -- Bill Frank
    Satellite -- Chris Velden
    Surface network -- Tom Schroeder
    Radar -- Mort Glass
1200 Lunch
1300 Working group meetings
1500 Working group reports
    Experimental Forecast Support -- Greg Holland
    Upper air network -- Johnny Chan
    Aircraft -- Hugh Willoughby
1930 Working group reports
    Data Management -- Ted Tsui
    Data sharing arrangements

Sunday 21 May 1989

0830 Working Group reports
    Experiment Operations Center
1000 Closing discussions
    Future plans
    Personnel requirements
    Budget requirements
    Operations Plan

APPENDIX C

Possible Structure of Field Experiment Plan (Outline)

1. Introduction and Executive Summary

1.1 Rationale and background

Background of overall research initiation
Objectives of overall initiative
Previous planning meetings
New research directions

1.2 Objectives of field experiment

Hypotheses

1.3 Climatology of events

1.4 Data requirements

New instrument platforms
Special data collections

1.5 Multi-agency participation

1.6 Field program, observing systems and networks

Map
List of observing systems
List of platforms
Soundings
    Land
    Shipboard
Radar wind profilers
Commercial aircraft
Buoys
Ships of opportunity

1.7 Management, routine activity and IOP activity

Experiment Operations Center
Steering Committee
International coordination
Forecast Office
Routine (non-IOP) activity
IOP schedules

1.8 Data Management

Data exchange procedures

1.9 Pre-experiment test

1.10 Supplementary information

1.11 Expected outcomes

Science
Short term benefit to operations during 1990 typhoon season
Transition to operations

1.12 References and Project Reports

2. Experiment Operations

2.1 Operational centers and personnel centers
Personnel
Sequence of events during IOP

2.2 Forecast center and personnel

Operations
- Non-IOP
- IOP

Incorporation of pre-experiment test results

2.3 Communications and information

2.4 Intra-experiment reviews

2.5 Data Center, Data Management Plan

3. Observing Systems and Activation Procedures

3.1 Soundings during non-IOP and IOP

Enhanced schedule for regular network
- International communications

Special experimental sites
- Maps

Shipboard
Aircraft
LORAN dropwindsondes
OMEGA dropwindsondes

3.2 Radar Wind Profilers

Existing sites
Special experimental sites
- Auxiliary instrumentation
  - Radiometers
  - RASS

3.3 Aircraft

General description of availability, flight personnel requirements/assignments
Operating limitations
Aircraft #1 - #N
- Instrumentation
- Schematic of aircraft instrumentation orientation
- Flight patterns for each hypothesis
  - Instrument deployments
- Plotting charts, supporting graphics and software
- Field operations
  - Facilities
  - Notification procedures
  - Briefings
  - Inflight responsibilities
  - Debriefings
  - Data Management
  - Communications
  - Security
  - Safety
  - Housekeeping requirements

3.4 Drifting buoys

Background description
Deployment pattern

3.5 Moored buoys

Japan (Typhoon Committee Operations Manual)
- Description
- Deployment

3.6 Land observations

3.7 Satellite

Platforms
Data collection
Products
- Real-time data
- Research sets
- Video tape

Archival
Distribution

3.8 Doppler radar

4. Data Management

4.1 Data management strategy

4.2 Real-time data management

4.3 Data programs

Collections, quality assurance, archival, distribution
Aircraft #1-#N
Soundings
- Regular
- Special sites
- Shipboard
- Aircraft

Radar wind profilers
Buoys
Land
Satellites

4.4 Data streams

Aircraft
Soundings
Radar wind profilers
Buoys
Land
Satellite
Project Operations
- Operations Center
- Forecast Center
- Aircraft Operations Center
- International Center

4.5 Data sets and Products

Field Program Summary Report
Data Users Guide
Intensive Observation Period Reports
- Operations report
- Synoptic charts and forecasts
- Satellite images
- Profiler data summary
- Data charts
- Airborne Mission Scientist reports

4.6 Data Users/Organizations

USA
International

5. Real-time modelling activities

USA
International

6. Miscellaneous

Telephone numbers
Lodging
Publicity
Safety procedures

7. Acronyms

APPENDIX D RESEARCH PROGRESS REPORTS

TROPICAL CYCLONE MOTION STUDIES
JUNE 1989

Roger K. Smith (Principal Investigator),

and co–workers

Michael J. Reeder and Wolfgang Ulrich
Meteorological Institute, University of Munich.

Early in 1989 we completed an analysis of high–resolution numerical simulations of the motion of nondivergent barotropic vortices on a beta plane, using diagnostic procedures suggested by the work of Kasahara and Platzman (1963). Both initially symmetric and asymmetric vortices were considered. The results form the basis of a paper submitted for publication (Smith and Ulrich, 1989). The work is being extended to the motion of vortices in spatially–varying environmental flows (Ulrich and Smith, 1989).

The former work has pointed a way to approximations that provide for the development of an analytic theory of vortex motion on a beta plane. These studies are continuing and a paper on the subject is currently under preparation (Smith, 1989).

In this latter work, the large–scale flows are modelled by stationary, single mode, finite amplitude planetary waves on a constant basic flow in a zonal channel, or simply by zonally–independent flows with sinusoidal cross–section in the meridional direction, the limiting case of a planetary wave with zero zonal wave–number. The formulation has been designed to focus on flows that are relevant to the important problem of understanding tropical cyclone recurvature. It turns out that the thumb rule that the vortex–drift locally has a component in the direction of the large scale flow and a component in the direction of the absolute vorticity gradient holds for all cases we have considered. To use this qualitative behaviour as a basis for a simple parmeterization of the vortex track requires some care. The speed and the direction of the vortex centre adjusts only gradually to the absolute vorticity gradient of the basic flow. This makes a track parameterization quite involved if the advection by the large scale flow is no longer dominant as in some experiments with the planetary wave. A prediction of the track using an average speed over a circle which covers the vortex core gives approximately the right local speed and direction of the vortex centre. This is supported by the fact that vortex and planetary wave patterns show relatively little interference.

In other work we have:

(a) Developed a three–layer two–dimensional shallow water wave numerical model on a β–plane to examine baroclinic aspects of hurricane motion. The model includes a simple parameterisation of convection;

(b) Developed a simpler one–dimensional version of the above model in order to map out the model parameter space and thereby provide guidence when conducting numerical experiments with the more comprehensive model;

(c) Re–coded the barotropic model on a Mecator projection. Output from this model was then used as input for Dr. S. Lord's objective analysis program. In this way it was possible to assess our present capability to detect the "beta–gyres" with the proposed observation network in the NW Pacific for the ONR experiment. The results, which are currently being written up, highlight the deficiencies in the data network for above purpose.

References:

Kasahara, A. and G.W. Platzman, 1963: Interaction of a hurricane with a steering field and its effect upon the hurricane trajectory. Tellus, 15, 321–335.

Smith, R.K. 1989: An analytical study of tropical cyclone motion using a barotropic model (in preparation).

Smith, R.K. and W. Ulrich, 1989: A numerical study of tropical cyclone motion using a barotropic model. Part I. The role of vortex asymmetries. (submitted to Quart. J. R. Met. Soc.).

Ulrich, W. and R.K. Smith, 1989: A numerical study of tropical cyclone motion using a barotropic model. Part II. Motion in spatially–varying large–scale flows. (to be submitted to Quart. J. R. Met. Soc.).

PROGRESS REPORT

R. Terry Williams
Melinda Peng
J. C.-L. Chan

Department of Meteorology
Naval Postgraduate School
Monterey, CA 93943

A nondivergent, barotropic analytical model scaled to approximate a tropical cyclone was used to show that the radial shear present in an axisymmetric vortical flow outside the radius of maximum winds acts to make the vortex barotropically stable with respect to small perturbations from axisymmetry (Carr and Williams, 1989a,b). This mechanism was isolated by using the Rankine vortex, which eliminated the possibility of neutral propagation or growth of the perturbations on the radial gradient of symmetric vorticity. The model was solved as an unforced initial-value problem, and it gave a perturbation streamfunction response that was asymptotically proportioned to t^{-2} for $t \rightarrow \infty$ in a manner analogous to the Couette flow problem. The rate of perturbation damping was proportional to the square of perturbation azimuthal wavenumber, which was consistent with observations that tropical cyclone asymmetries are predominantly azimuthal wavenumber-1 in structure. The rate of damping was also proportional to the square of the local radial shear of the symmetric angular wind, which may explain in part why tropical cyclones become increasingly axisymmetric as the center is approached. The agreement of these results with both numerical and observational evidence suggests that the stability of tropical cyclones and dynamically similar vortices is due principally to this barotropic stability mechanism. The stability mechanism was also analyzed in terms of barotropic energy transfer principles, and the contribution of perturbation momentum flux convergence to the strength of the mean vortex was calculated.

The asymmetric structure of a vortex moving on the Beta-plane was studied with the nondivergent barotropic vorticity equation which was linearized with respect to the symmetric part of the vortex (Peng, 1989 and Peng and Williams, 1989a,b,c). The total system was transformed to a coordinate system moving with the vortex. The direction and speed of the movement were specified using the data from full nonlinear model results. For a commonly used asymmetric radial wind profile, a sign change in the vorticity was shown to give

barotropic instability. Two different gyres were obtained for wavenumber-1 around the vortex. The inner gyre was the unstable mode with maximum amplitude located at the radius of maximum wind. The outer gyre, whose orientation was along the track direction specified by the movement, corresponds very closely to the Beta-gyre obtained in the numerical model. The strength of the inner gyre was much larger than the outer gyre. For the steady-state solution with high finite difference resolution, only the inner gyre was present, and it was oriented in the northeast direction unless the speed of translation was very large. The outer Beta-gyre was isolated by placing a new boundary a few points from the center or by reducing the resolution so the associated instability was reduced. The asymmetric circulation thus obtained has the correct orientation and magnitude when compared to the solutions of the full nonlinear model. The time-dependent linear model gives results that are consistent with the steady state solutions.

In addition, the steady state equation for the asymmetric circulation was solved analytically for certain vortex wind profiles (Carr, 1989). These profiles generally resembled the ones used in the numerical models, but they contained jumps in vorticity gradient. These solutions showed the beta-gyres with proper orientation and strength. It was shown that the circulation equation was not valid in the outer region because the linearization could not be justified there. Various outer boundary conditions were examined and results were found to be sensitive to them.

Numerical studies of vortex motion with background basic currents were carried out with the full numerical model (Chan and Williams, 1989). Linear and parabolic environmental winds were investigated. Linear and nonlinear solutions were compared as was done by Chan and Williams (1987).

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Carr, L. E., 1989: Vortex adjustment and motion in response to asymmetric forcing with application to tropical cyclones. Doctoral dissertation, Naval Postgraduate School, September 1989.

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Peng, M. S., and R. T. Williams, 1989c: Instability of the tropical cyclone radial profile and its association with cyclone movement. 7th Conference on Atmosphere and Oceanic Waves and Stability, San Francisco, 10-14 April.

Peng, M. S., 1989: Dynamics of vortex motion on a tropical beta-plane. International Conference on East Asia and the Western Pacific, Hong Kong, 6-8 July.

WORK REPORT JUNE 1989

PI Greg J. Holland

Overview

Research has continued on modelling and observational studies of tropical cyclone motion mechanisms, on the potential degree of uncertainty in cyclone prediction and on the isolated nature of tropical cyclones. Considerable effort has been devoted towards general planning for the 1990 field experiment. The development research for workstations in tropical cyclone forecasting has been extended to include work on the use of expert systems and the potential use of Markov chain and other statistical techniques.

1. Interaction of Cyclones with the Subtropical Ridge (G. Holland J. Evans, R. Elsberry)

The barotropic modelling study of the interaction of a barotropic vortex with an idealised subtropical ridge and monsoon trough is nearing completion (Evans et al., 1989: Holland and Evans, 1989). We have found that for a single vortex configuration the speed of propagation is a quasi-linear function of the absolute vorticity gradient of the environment. We have further shown that actual relative vorticity gradients can exceed and oppose the earth gradient so that a considerable range of propagation velocities are possible. We are now testing the model results using AMEX and composite cyclones. Attempts to separate the vortex and environment using the current observational method leads to considerable degradation of the signal, however, indicating a need for further refinements to the observational method.

2. Motion of a Baroclinic Vortex in a PE Model (G. Holland, R. Hodur)

This study is now completed (Holland and Hodur, 1989). The major finding was that the vortex propagation was defined by the structure in the lower troposphere. Upper tropospheric evolution of an outflow regime had little effect on the vortex propagation.

3. Experiments with the BMRC Tropical Model (L. Leslie, G. Holland)

The study on the effects of perfect boundary conditions on model predicytions of the AMEX tropical cyclones has been completed. Our findings are that the use of weighted analysis conditions at the outer few grid points provides a powerful constraint on the internal prediction. We consider that suitable selection of weighting for analysis and model predictions in a nuding type assimilation scheme may be a viable method of 'bogussing' in the tropical ctyclone core. Further numerical experiments are on hold while the model is upgraded. Physical process are being adjusted, the initialisation has been changed from normal mode to dynamical, and the model grid has been modified to allow predictions anywhere on the globe. The model also has now been transferred to the Bureau of Meteorology supercomputer.

4. Isolated Nature of Tropical Cyclones (G. Holland, R. Elsberry

This study is proceeding slowly. The observational data examined to date indicate that tropical cyclones are not isolated in the manner defined by Flierl. Further, an examination of the evolution of a single vortex in a PE model indicates that the vortex angular momentum increased substantially during the integration. Further work is required before any definitive conclusions can be made. But care needs to be taken with literal translation of barotropic results to baroclinic systems.

5. Multiple Vortex Interaction (G. Holland, L. Leslie, G. Dietachmayer)

This is a combined dynamical systems and barotropic modelli analysis of the manner in which meso-synoptic scale vortices interact. The dynamical systems analysis follows the classical method of interacting point vortices, but is generalised to include finite sized (but not deformable) vortices that propagate on the vorticity gradient of all other vortices in the domain. Propagation is defined by the linear regression equations developed by Evans et al. (1989). It has been shown that when propagation is included all multiple vortex interactions are potentially chaotic and contain multiple equilibria solutions. Many thousands of simulations have been made to examine the basic types of attractors, the extent of their basins of attraction and the locations of bifurcation regions (Holland, 1989). These results are being used to define simulations to be run on the barotropic model to test the validity of the simple dynamical systems analysis (Leslie et al., 1989).

6. Field Experiment Planning (G. Holland)

A lot of effort has been devoted to planning for the 1990 field experiment. This includes helping Russ Elsberry and Bob Abbey with coordination with the Typhoon Committee countries, Russia and Taiwan; establishment of the forecasting office in JTWC; and purchase and deployment of a Doppler profiler in collaboration with NOAA Aeronomy Laboratory and Penn State University.

7. Work Station Development (G. Holland, F. Woodcock, S. Ng, L. Leslie)

A tropical cyclone workstation is being developed in collaboration with the services arm of the Bureau of Meteorology (Holland et al. , 1989). Significant developments include the applications of numerical models to a workstation environment and the development of specialised statistical techniques, including Markov chain, and optimal linear combination (Leslie and Fraedrich 1989) to forecasting in a workstation environment (Leslie et al., 1989). We are about to start a collaboration with H-H. Dai from the Institute of Atmospheric Physics, Beijing on the application of expert system analysis techniques to tropical cyclone forecasting. The PTCM87 technique was given a successful trial last summer season in the Australian region. Our aim is to test many of these ideas as part of the forecasting effort in the 1990 field experiment.

Recent Publications and Conference Reports

Chan, J.C.L. and G.J. Holland, 1989: Observing tropical cyclones: Where next? Bull. Amer. Met. Soc., (submitted).

Evans, J.L., 1989: Interactions between a barotropic vortex and an idealised subtropical ridge. 18th Technical Conference on Hurricanes and Tropical Meteorology, San Diego, May 1989.

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Leslie, L.M. and K. Fraedrich, 1989: The reduction of mean position error of Australian region tropical cyclones using optimal combinations of independentforecasts. Mon. Wea. Rev., (submitted).

Velden, C.S. and G.J. Holland, 1988: Barotropic numerical modelling studies of tropical cyclone motion during AMEX. Mon. Wea. Rev., (submitted).

Progress Report

Tom Schroeder
Bin Wang
Mark Lander
University of Hawaii

Our work has had two components: observational and modeling.

1. Observational Studies.

We have analyzed the synoptic environment surrounding several typhoons in the Philippine Sea. Due to data availability our analyses have been limited to the surface and upper-troposphere. The focus of the effort has been Typhoon Irving, 1979. Irving was a "through the ridge" case according to the Sandgathe classification. Irving had a much more complicated life than was evident at first glance. Among the complications was an unnamed storm that formed east of Japan under a cut-off low aloft.

In support of planning for the 1990 experiment we have analyzed the structure of the sub-tropical ridge during July and August using the FGGE level 3-B data set. The ridge typically sits along 30-33 N over the northern Philippine Sea although significant excursions do occur. Vertically it is rather erect.

2. Modeling Studies.

Typhoon Irving. The dry model of the FSU regional model has been used to simulate the motion of Irving using FGGE 3-B as initial conditions and boundary forcing. 84-hour simulation indicates that the model captures many realistic features including recurvature at hour 48. We tested the sensitivity of model results to vertical resolution (2, 3, 6 and 10 levels, respectively) and found that the 6 and 10 level model results were quite similar but both were superior to lower resolutions.

Ideal case modeling. We have tested the model using "fixed" and "sponge layer" boundary conditions for idealized vortex motion. Initially, no environmental flow was included. We have tested sensitivity of 48-hour forecasts to domain size, boundary conditions, vertical and horizontal resolution, and viscosity. From these control experiments, we plan to investigate carefully the basic factors that may affect Beta-drift and the effects of interaction of vortex flow with an environmental flow.

Progress Report

Russell L. Elsberry
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Two papers (Fiorino and Elsberry 1989a, b) have been published recently. The first paper examines the role of vortex structure in tropical cyclone motion. A physical interpretation of the different track responses has been given in terms of the symmetric vortex circulation relative to the tropical cyclone center. The major features in the asymmetric circulation are the anticyclonic and cyclonic gyres to the east and west of the center respectively. The flow between these large-scale (~ 600 km) counter-rotating gyres is the primary factor in the advection of the symmetric vortex. However, the symmetric vortex circulation distorts the large-scale gyres, especially in the high wind speed regime near the center. The amount of cyclonic distortion of the large-scale gyre circulation is proportional to the outer (300-800 km) wind strength in the tropical cyclone. Consequently, both the strength and orientation of the -effect are determined by the initial vortex structure (Fiorino and Elsberry 1988).

The Fiorino and Elsberry (1989b) paper deals with the implications of the initial bogus vortex specification for numerical prediction of tropical cyclone tracks. This study uses two-dimensional Fourier analyses of different initial vortex structures to indicate the relative contributions of small (< 500 km), medium (500 to 1500 km) and large (> 1500 km) scales. Whereas the large scales primarily determine the speed of the -effect, the orientation of the -effect deviation from the steering flow is due to the medium and small scales. This information should provide useful guidance for improving the initial bogus vortex specification in the present numerical track prediction models.

To test the theories of vortex motion due to variations of the Coriolis parameter and environmental vorticity, Carr and Elsberry (1989) have examined observations of tropical cyclone motion relative to computed "steering flows" using previously published composite data. The "propagation vector" defined as the vector difference between the tropical cyclone motion and the steering generally supports recent nonlinear numerical results such as: (i) the general magnitude and direction of the beta-induced motion; (ii) the dependence of the beta-effect on vortex outer-wind strength; and (iii) the dependence of vortex motion on the direction of the environmental vorticity gradient.

The influence of the environmental vorticity gradient has been explored with a shallow-water equation model by Evans, Holland and Elsberry (1989). Changes in tropical cyclone motion for cyclones placed in the monsoonal trough, between the monsoonal trough and the subtropical ridge and poleward of the ridge are compared with an isolated vortex in a no-mean flow environment. Both the propagation and the symmetric gyre structure are considerably modified by the ridge environment. The simulated tracks are consistent with the observations described by Carr and Elsberry (1989).

One of the special problems in tropical cyclone motion facing the western North Pacific forecaster is the interaction of vortices (Sandgathe 1987). Gunzelman (1989) has addressed the general problem of tropical cyclone motion due to environmental interactions by representing operationally-analyzed vorticity fields in terms of empirical orthogonal functions. This representation provides a smoother and more dependable depiction of the vorticity dynamics than with the original vorticity fields, such as used by Sherman (1988). Five processes that contribute to motion relative to the steering flow during periods of interaction with adjacent circulations are evaluated for their contributions to binary rotation and to changing the separation distance between the interacting circulations. The Fujiwhara effect and the convergence effect of the tropical cyclone on the adjacent feature seem to be the most applicable processes. The environmental shear effect applies only in special conditions.

Another thrust in the research has been to explore the applicability of an Isentropic Potential Vorticity (IPV) representation during tropical cyclone recurvature, which is another difficult forecast problem (Sandgathe 1987). The IPV fields have proven to be very useful for describing midlatitude circulations, especially midlatitude troughs and jet streak dynamics. Thus, the objective of the M.S. thesis of Boerlage (1989) is to examine the IPV fields during recurvature when the tropical cyclone interacts with midlatitude features. Since the observational network does not have the requisite horizontal and vertical resolution, the first test is with the output of the Advanced Tropical Cyclone Model (ATCM). One of the first results is that the bogus vortex inserted in the ATCM leads to unstable IPV conditions and a traumatic adjustment occurs in the model vortex to eliminate the instability. After this 24-h adjustment period, the IPV advection pattern clearly indicates the path of the tropical cyclone. It is hoped the observations to be obtained in the 1990 field experiment will allow a validation of this advective process.

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SUMMARY OF W. M. GRAY'S ONR SPONSORED TROPICAL CYCLONE MOTION RESEARCH AND FUTURE PLANS

By
William M. Gray

July, 1989

The author and his project personnel have been performing a varie of Tropical Cyclone (TC) motion related research. Our basic research purpose, in line with the ONR research mission, is to try to increase our understanding of the theory of TC motion. This research consists a careful analysis of: 1) TC motion versus the cyclone's steering current at various radii, and 2) the physical process which best distinguish TC recurvature from non-recurvature as measured by rawinsonde, aircraft, and digitized satellite data.

A fuller description of the author's project research was given i a 121 page write-up entitled "Tropical Cyclone Motion Research-Observation and Physical Implications" by W. Gray, et. al. (1988) with accompanying 150 pages of TC motion data that was handed out at the ON sponsored Rainbow Beach, Australia meeting of 29 June-1 July 1988. Another more graphical 50-page report was handed out at the ONR San Diego meeting in May of this year.

Background

One of our major efforts of the last year has been to develop new software programs that are specifically designed to best portray the desired wind and height fields associated with TC motion. This has

taken a lot of software developing and testing. One full time programmer, 1-2 graduate students, and the author has been involved in this endeavour. These new software programs have now been run on 56 separate TC motion classes stratified by speed (typically 4 categories), direction (typically 3 categories), and intensity (typically 3 categories) in the three ocean basins of the NW Pacific, Atlantic, and SW Pacific. Stratifications are listed in the beginning of the tables of Appendix A. Soundings include all rawinsonde data for 21-year period in all three ocean basins. The typical stratification has about five thousand soundings within 11° radius.

Data have been layer averaged by mass as follows: 850-300 mb, 700-500 mb, 1000-100 mb, 300-100 mb, and 50-100 mb. Data have then been azimuthally divided into front, back, right, and left quadrants, in the Natural (geographical), Rotated (ROT) and MOTion-ROTated (MOTROT) coordinate systems. Wind components at each 2° radial belt and azimuthal quadrant has been broken down into parallel and normal components to the TC direction of motion.

Surrounding cyclone winds have been vectorially averaged by two degree radial belts 1-3° or 2° radius, 2-4° or 3° radius, 3-5° or 4° radius, 5-7° or 6° radius, etc. Analyses goes out to 11° radius. These outer radius surrounding cyclone wind vectors are then compared with the cyclone vector motion. Following the suggestion of Elsberry-Carr we designate the mean vectorial wind in the 5-7° radius and 850-300 mb layer as the "standard" steering wind vector. We then compare the TC motion vector and the other radii wind vectors to this standard steering current. Figures 1 and 2 show typical 850-300 mb steering of motion

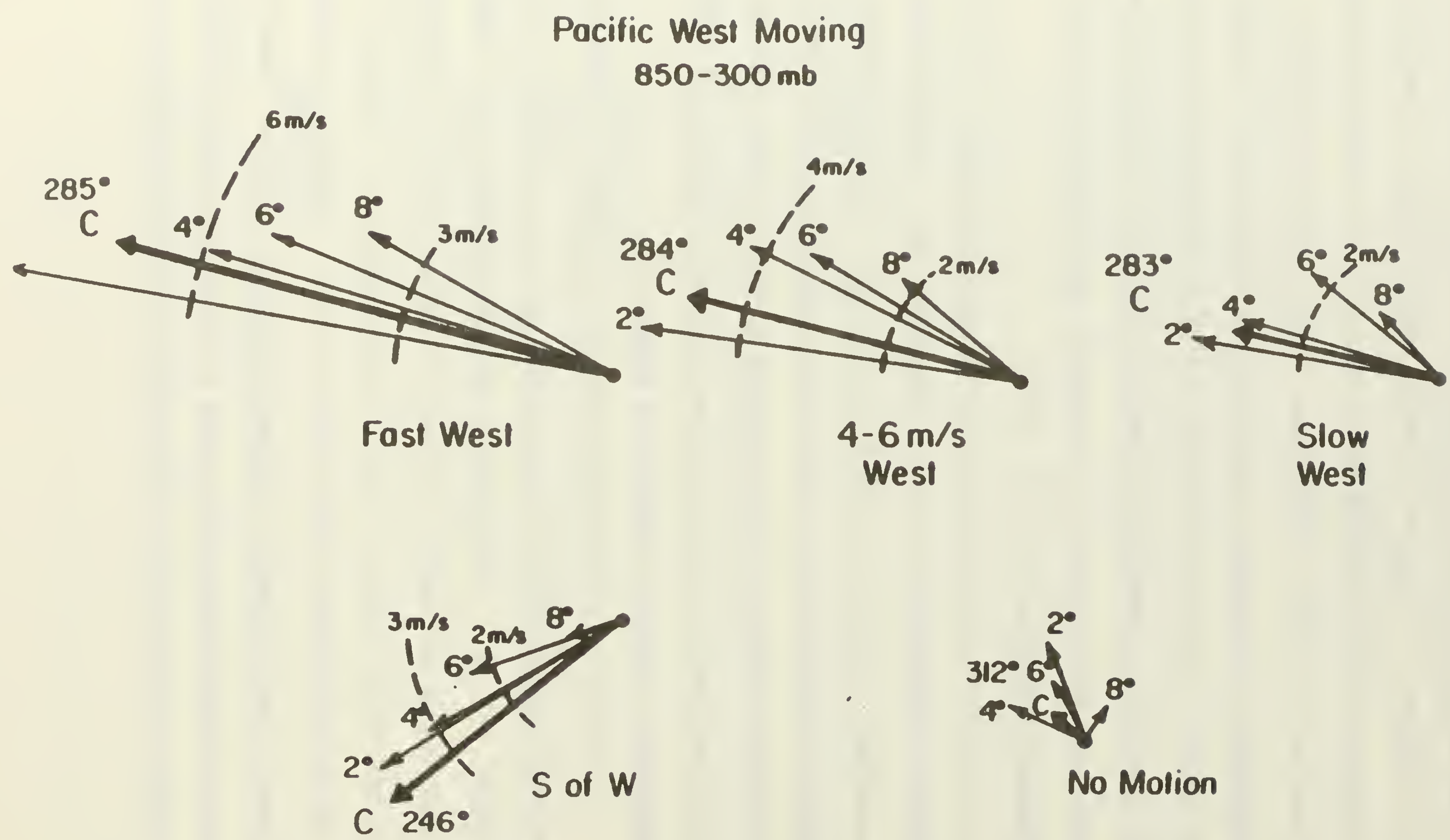

Fig. 1. Layer average (850-300 mb) symmetric wind vectors in various radial bands relative to the mean cyclone motion (C). Stratifications are by cyclone speed for West moving (direction in degrees) NW Pacific motion cyclones. 2° is 1-3° mean motion, 4° is 3-5° mean motion, etc.

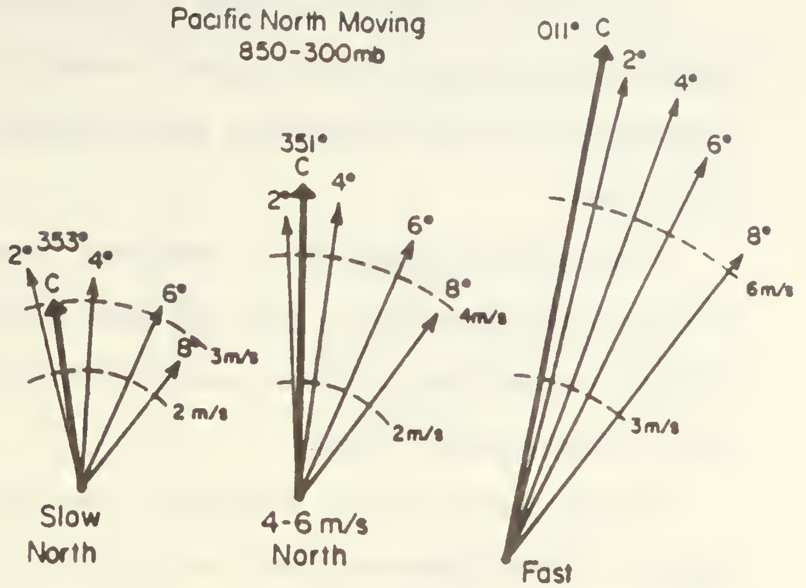

Fig. 2. Same as Fig. 1, except for North moving cyclones.

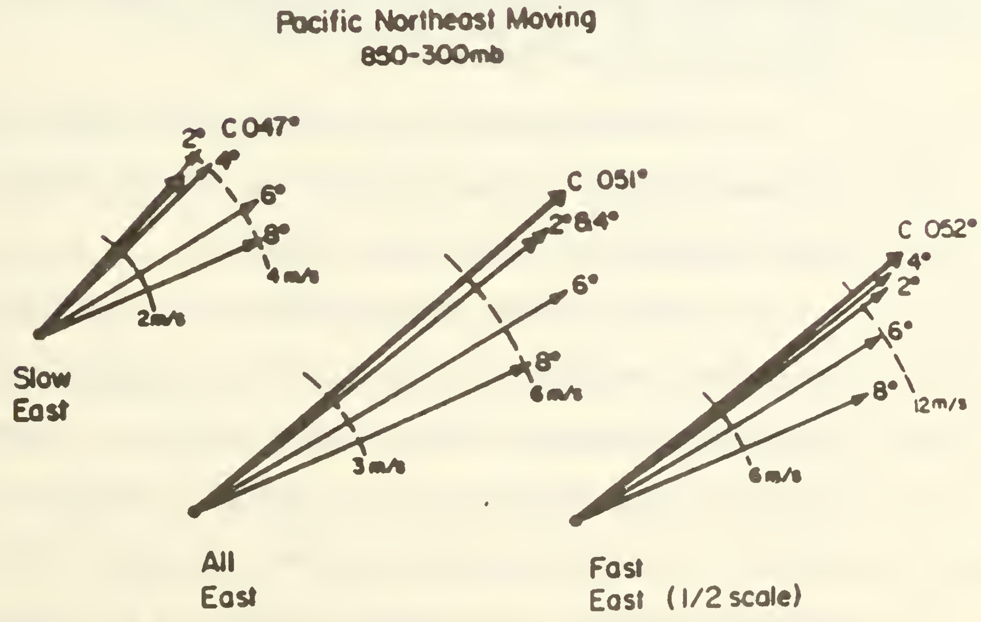

Fig. 3. Same as Fig. 1, except for Northeast moving cyclones.

vector differences for NW Pacific cyclones.

We have also studied the Right to Left and Front to Back height gradients across the various composite stratifications to verify wind information and learn of interior versus exterior radius height gradient differences.

A primary new feature of our analysis is the study of the TC's interior steering current. This has never before been explicitly isolated and analyzed in comparison with the cyclone motion and the other radius steering current.

Another feature of our analysis is the study of interior versus exterior radius Right minus Left and Front minus Back quadrant wind asymmetry in the MOTROT coordinate system.

<u>Data Implications</u>. We have put our major effort over the last year at processing our data sets and are only now turning more of our attention to the physical implications of these results. New findings from these analyses indicate that

1. TCs move faster and generally to the left of their outer radius mean steering (5-7° radius, 850-300 mb) current because their interior steering current is faster and to the left.

In a general sense, TC a-steering (or propagation) results from Right minus Left and Front minus Back wind asymmetries which occur in the MOTROT coordinate system as shown in Fig. 4. These MOTROT tangential wind asymmetries are a natural consequence of the TC's faster interior to external steering current. At inner radius (1-3°) MOTROT winds are stronger on the right and front of the vortex. At outer (5-7°) radius MOTROT winds are strongest on the left and back quadrants.

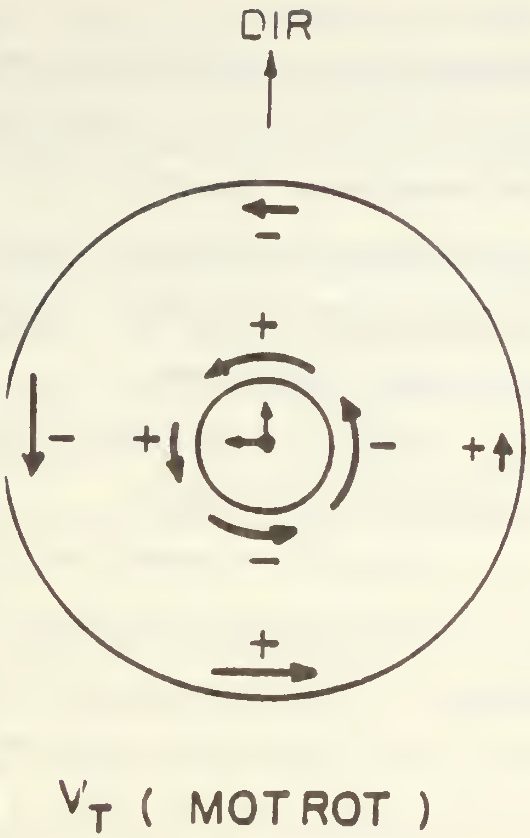

Fig. 4. Depiction of the tangential wind asymmetry associated with a TC in the MOTROT coordinate system. Note the differences in right-left and front-back inner and outer radius asymmetries.

This causes the interior vortex to move forward and to the left relative to the outer vortex. Vortices move in response to their MOTROT asymmetries. A stronger right than left quadrant MOTROT wind causes greater front than back quadrant vorticity advection and a forward vortex propagation. Similarly, a stronger front than back quadrant MOTROT wind causes a left vorticity advection and vortex propagation to the left. The center of the tropical cyclone closely follows the motion of the interior 1-3° radius vortex. If the 1-3° vortex moves faster and to the left of the 5-7° vortex so then too will the TC center. This is the propagation influences. These inner versus outer-core MOTROT wind

asymmetries occur in nearly all our motion stratifications. They are a consequence of the tropical cyclone center existing in a stronger part of the broader-scale steering current than the outer radius vortex flow. TC a-steering (or propagation) is thus primarily a consequence of vortex surrounding current interaction - not so much a Beta influence as has been previously hypothesized.

2. A-steering differences are about the same for levels of 850-300 mb, 1000-100 mb, or 700-500 mb.

3. Changes in TC movement are primarily related to changes in outer (6° radius) versus inner radius (2° radius) tangential wind asymmetry. A trough impinging on the poleward side of a TC will throw the usual inner versus outer radius MOTROT asymmetry pattern out of balance and cause the outer vortex to move differently to the inner vortex. These changing outer radius asymmetries will propagate in 1-2 days to inner radius and cause the inner radius asymmetries and the TC center to then alter the cyclone's course.

4. TC a-steering is not appreciably influenced by differences in TC intensity and outer wind strength. Strength of 1-3° radius outer vortex does not lead to stronger a-steering current motion as some previous model results have indicated.

5. Pacific versus Atlantic a-steering differences for west moving TCs attest to the role of different environments on a-steering - in contrast to the Beta influence. The Atlantic does not have a monsoon trough. There are greater front minus back MOTROT wind asymmetries in the Atlantic than in the Pacific. This causes west moving Atlantic TCs to deviate less to the left of their steering current than NW Pacific

west moving cyclones. Except for West moving Atlantic cyclones which do not much deviate to the left, all other composites follow a similar pattern for west, south of west, north, and NE moving cyclones.

TC Recurvature.

As a separate motion topic we are putting a great deal of effort in the recurvature question. We are contrasting recurvature versus non-recurvature cases. Recurvature is being broken up into sharp and gentle turning cases. We are also looking at cases of longer northward tracks, and also the tracks of cases which begin to recurve and then turn leftward.

We find that the major distinguishing factors between these recurving versus non-recurving conditions 1-3 days before recurvature are found on the north side of the cyclone (this is well known) but in the very upper troposphere and lower stratosphere. The high level aspects of recurvature has been less appreciated. Recurvature does not occur until upper-tropospheric outflow has been altered. Cyclone motion change appears to best respond to upper tropospheric-lower stratospheric wind changes. Upper level information is much more of a distinguishing factor than 500 and 700 mb level data which have been more commonly used in recurvature forecasting.

Future Effort

We will more thoroughly synthesize our new rawinsonde stratifications. There is much more to be accomplished with the height fields and in the upper-troposphere analyses. We hope to make many more computer runs of the future 24-48-72- hour changes in wind-height fields from current conditions for cyclones that undergo different 1-3 day

future motion track changes. For instance, what are the typical 48 hou future outer radius wind and height changes from current analysis that occur with systems which we know will continue to move straight versus those that we know will undergo change in direction or speed? This information may help in the establishment of better empirical uses of the GCM track progs. I see many beneficial new insights and practical uses to be derived from our rawinsonde analyses. I believe these rawinsonde data sets can be utilized to develop improved TC track forecast schemes which utilize GCM progs in combination with empirical information. We are specifically planning to use our rawinsonde data sets to develop improved methods of predicting recurvature versus non-recurvature.

We are also planning to extensively analyze recent year ECMWF forecasts of TC motion to try to better verify and understand how well the global modeling efforts are proceedings.

APPENDIX (M.

PACIFIC MOTION COMPOSITES

Stratification Description	Stratification Speed Class	Stratification Direction	Criterion Speed(knots)	No. of Sounding
WP180	Slow West	240<=DIR<315	4<=SPD<=7	18595
WP181	Fast West	240<=DIR<315	SPD>11	31184
WP182	Slow North	315<Dir or Dir<045	4<=SPD<=7	21945
WP183	Fast North	315<Dir or Dir<045	SPD>11	23477
WP184	No Motion		0<=SPD<=3	9125
WP185	All West	240<=DIR<315		81302
WP186	All North	315<Dir or Dir<045		72841
WP187	Imm. West	240<=DIR<315	8<=SPD<=11	28673
WP188	Imm North	315<Dir or Dir<045	8<=SPD<=11	23881
WP189	All NE	020<=DIR<090		38086
WP190	Fast NE	020<=DIR<090	SPD>17	10573
WP191	Slow NE	020<=DIR<090	SPD<12	19102
WP192	All SW	210<=DIR<260		10623

INTENSITY

Stratification Description	Stratification Direction	Criterion Speed(knots)	Stratification Intensity Class	Lat	No. of Sounding
WP200	240<=DIR<330	SPD>=4	980<=MSLP<=1000	Lat<=35	38759
WP201	240<=DIR<330	SPD>=4	955<=MSLP<=980	Lat<=35	9653
WP202	240<=DIR<330	SPD>=4	MSLP<=955	Lat<=35	16775
WP203	240<=DIR<330	SPD>=4	970<=MSLP<=1000	Lat<=35	50841
WP204	240<=DIR<330	SPD>=4	MSLP<=970	Lat<=35	26632
WP205	340<=DIR<090	SPD>=4	970<=MSLP<=1000	Lat<=40	25052
WP206	340<=DIR<090	SPD>=4	MSLP<=970	Lat<=40	16739

Fig. 1 Listing of differnt West Pacific rawinsonde composite motion stratifications - top diagram, and similar rawinsonde by cyclone intensity - bottom diagram, data has been stratified by direction, speed, and intensity. The number of soundings in each stratification are also shown.

ATLANTIC MOTION COMPOSITE

Stratification Description	Stratification Speed Class	Stratification Direction	Criterion Speed(knots)	No. of Soundings
WI070	Slow West	240<=DIR<315	4<=SPD<=7	1602
WI071	Fast West	240<=DIR<315	SPD>11	1507
WI072	Slow North	315<Dir or Dir<045	4<=SPD<=7	2913
WI073	Fast North	315<Dir or Dir<045	SPD>11	1767
WI074	No Motion		0<=SPD<=3	1918
WI075	All West	240<=DIR<315	SPD>=4	5023
WI076	All North	315<Dir or Dir<045	SPD>=4	7030
WI077	Imm. West	240<=DIR<315	8<=SPD<=11	1914
WI078	Imm North	315<Dir or Dir<045	8<=SPD<=11	2350
WI079	All NE	020<=DIR<090	SPD>=4	6000
WI080	Fast NE	020<=DIR<090	SPD>17	1333
WI081	Slow NE	020<=DIR<090	4<=SPD<12	2931
WI082	All SW	210<=DIR<260	SPD>=4	1179

INTENSITY

Stratification Description	Stratification Direction	Criterion Speed(knots)	Stratification Intensity Class	Lat	No. of Soundi
WI090	240<=DIR<330	SPD>=4	990<=MSLP<=1005	Lat<=35	83
WI091	240<=DIR<330	SPD>=4	965<=MSLP<=990	Lat<=35	78
WI092	240<=DIR<330	SPD>=4	MSLP<=965	Lat<=35	82
WI093	240<=DIR<330	SPD>=4	980<=MSLP<=1005	Lat<=35	121
WI094	240<=DIR<330	SPD>=4	MSLP<=980	Lat<=35	122
WI095	340<=DIR<090	SPD>=4	980<=MSLP<=1005	Lat<=40	191
WI096	340<=DIR<090	SPD>=4	MSLP<=980	Lat<=40	102

Fig. 2 Same as Fig. 1, except for Atlantic data set.

SOUTH PACIFIC MOTION COMPOSITES

Stratification Description	Stratification Speed Class	Stratification Direction	Criterion Speed(knots)	No. of Sounding
SP020	No Motion	150<=DIR< 315	SPD< 3	3673
SP021	Slow East	045<=DIR<=150	3<=SPD<=6	4465
SP022	Fast East	045<=DIR<=150	SPD> 6	6549
SP023	Slow West	210<=DIR<=315	3<=SPD<=6	5811
SP024	Fast West	210<=DIR<=315	SPD> 6	6745
SP025	Slow South	135<=DIR<=225	3<=SPD<=6	3289
SP026	Fast South	135<=DIR<=225	SPD> 6	3601
SP027	All East	045<=DIR<=150	SPD> 2	9298
SP028	All West	210<=DIR<=315	SPD> 2	10760
SP029	All South	210<=DIR<=315	SPD> 2	7722

INTENSITY

Stratification Description	Stratification Direction	Criterion Speed(knots)	Stratification Intensity Class	Lat	No. of Sounding
SP030	Weak East	SPD> 2	990<=MSLP<=1005	Lat<=30	3268
SP031	Strong East	SPD> 2	MSLP< 990	Lat<=30	1474
SP032	Weak West	SPD> 2	990<=MSLP<=1005	Lat<=30	3187
SP033	Strong West	SPD> 2	MSLP< 990	Lat<=30	1789
SP034	Weak South	SPD> 2	990<=MSLP<=1005	Lat<=30	2111
SP035	Strong South	SPD> 2	MSLP< 990	Lat<=30	1491
SP036	East Moving	SPD> 2	990<=MSLP<=1005	Lat<=15S	1495
SP037	West Moving	SPD> 2	990<=MSLP<=1005	Lat<=15S	1929
SP038	South Moving	SPD> 2	990<=MSLP<=1005	Lat<=15S	810

Fig. 3 Same as Fig. 1, except for South Pacific data set.

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